Final Report

Process improvements for preserving peak freshness in broccoli (2)

Jenny Ekman
Applied Horticultural Research

Project Number: VG14062

VG14062

This project has been funded by Hort Innovation using the research and development vegetable levy and funds from the Australian Government.

ISBN 978 0 7341 4356 3

Published and distributed by:
Hort Innovation
Level 8, 1 Chifley Square
Sydney NSW 2000
Tel: (02) 8295 2300
Fax: (02) 8295 2399

Contents

Summary

Despite broccoli's image as a healthy, nutritious and flavoursome vegetable, sales are constrained by poor quality at retail and disappointing storability after purchase. A series of trials have been conducted examining how harvest, cooling and handling practices within supply chains could be affecting broccoli freshness at retail. Quality attributes including colour, rots and overall acceptability were assessed during storage at 7 or 16°C, these being the average temperature of broccoli in refrigerated and non-refrigerated retail displays.

Storage quality was unaffected by time of harvest (6:00, 11:00 or 16:00) in Gatton during spring, even though soluble solids (including sugars) were significantly higher in broccoli harvested in the late afternoon. Late harvested heads also gained little weight during hydro-vacuum cooling, whereas those harvested in the morning gained 1−3%. This was the opposite result to what had been expected, and suggests that either the broccoli failed to fully hydrate overnight or that increased stomatal opening in the cool morning increased permeability to water.

Trials also examined the effect of cooling method (room cooling, hydro-cooling and hydro-vacuum cooling) on broccoli quality after transport to Sydney from Gatton (1 day) or Manjimup (1 week). The major differences were in weight gain or loss. Broccoli absorbed 2−7% moisture during hydro-vacuum cooling and hydro-cooling, a difference that was retained through to the end of storage life and is likely to improve head firmness. Although differences due to cooling method were not significant, this is likely due to cool harvest temperatures and the small quantities used for room cooling. There is considerable anecdotal evidence indicating that faster cooling does result in fresher broccoli at retail.

Delays between harvest and cooling greatly increased weight loss and reduced broccoli storage and shelf life. Differences were increased when broccoli was stored for an extended period and subjected to fluctuating temperatures within the supply chain – as occurred during transport from Manjimup to Sydney. All of the samples appeared in generally good condition on arrival, however clear differences appeared during storage at 7°C.

Two trials (Werribee and Manjimup) tested the effects of the new SmartFresh® In-Box system on broccoli quality. In-Box is a new delivery system for the ethylene antagonist gas 1-methylcyclopropene (1-MCP). It is best combined with a RipeLock liner, which is less permeable to 1-MCP than standard LDPE film. Four In-Box sachets were added to broccoli packed in standard LDPE or RipeLock liners, either immediately after pre-cooling or following overnight storage. Results were compared to broccoli packed in liners alone, or in top iced styrofoam cartons.

In both trials, broccoli quality using the SmartFresh In-Box system was similar to broccoli that had been top iced. Differences were greatest in broccoli transported from Manjimup to Sydney; top icing kept broccoli cold, whereas samples packed in cardboard cartons with liners averaged 5−10°C or even higher for nearly a week. Despite this abuse, SmartFresh® combined with a RipeLock liner protected the broccoli from yellowing and resulted in equivalent quality to the ice-packed product. The results suggest that SmartFresh In-Box could offer an alternative to ice in situations where the cold chain is imperfectly maintained.

Keywords

Broccoli, Postharvest, Storage, Transport, Cooling, 1-MCP, SmartFresh, In-Box, AgroFresh, Ice, Hydro-vacuum, Hydro-cooling, Delay, Energy

Introduction

Broccoli is almost universally regarded as a healthy, tasty vegetable. Stir-fried, steamed, microwaved, added to soups or even baked, broccoli can add variety to many meals. Certainly consumption has increased greatly over the last 30 years, as many consumers seek the flavour, colour and potential health benefits that broccoli provides.

However, consumer research conducted as part of VG12045 found that although consumers like and want to purchase broccoli, poor and inconsistent quality is a major barrier to increased consumption. Quality issues included not just appearance at the retail display, but lack of storage life after purchase[1].

These findings were supported by project VG13086, which surveyed broccoli quality in-stores, and examined the effectiveness of a number of supply chains. This research indicated that broccoli freshness at retail is highly variable. Quality did not relate to display method or price, and storage life could not be easily predicted from quality at purchase. It was concluded that consumers were likely to be disappointed in broccoli quality approximately one shopping trip in four[2].

Broccoli is a rapidly developing head. It has little protection against moisture loss, few storage reserves, and is very sensitive to external ethylene. Temperature is critical to preserving broccoli in its best possible condition. Many growers still pack broccoli in ice in order to protect it from temperature fluctuations in supply chains. However, ice adds significant cost in terms of power consumption, water use, labour and transport. The styrofoam packaging required is expensive and not easily recyclable. Moreover, if the ice melts, the result can be increased stem splits and rots.

This project has examined some of the factors that could increase or decrease the retail freshness of broccoli. These include harvest time, delay before cooling, cooling method and packaging materials. We have also tested a novel method of reducing yellowing of broccoli – the SmartFresh® In-Box system – with a view to keeping broccoli fresh during storage, transport, retail display, and even once it reaches the consumers fridge.

[1] Hamblin D, Todd S. 2013. Project Hurdle. Understanding the attributes that inhibit the purchase and consumption of vegetables: broccoli. Final Report VG12045 Horticulture Australia Ltd.

[2] Ekman JH. 2014. Identify process improvements for preserving peak freshness of broccoli. Final Report VG13086 Horticulture Australia Ltd.

Methodology

The initial task was to review available information on how broccoli is cooled and packed in other countries. Sources of information included peer-reviewed literature, research contacts, commercial wholesalers and direct communication with growers.

In addition, the energy costs of different cooling methods for broccoli were analysed. These calculations assume a field temperature of 20°C and desired final temperature of 4°C for one tonne of broccoli. The estimated thermal conductivity of broccoli, average head size and stalk thickness and total sensible heat removed by each system are used in this analysis. The energy efficiency of forced air, hydro-cooling, room cooling, top icing and vacuum cooling are compared.

A series of trials were then conducted examining the factors that can impact on broccoli quality in typical Australian supply chains.

Trial 1 examined the effect of harvest time on broccoli quality attributes. Broccoli was harvested at 6:00, 11:00 and 16:00 on 2nd September at a commercial vegetable farm in Gatton, Qld. Broccoli heads were selected so as to be of approximately equal size and maturity when cut.

Twenty individual heads were used to measure stem soluble solids and head density. Soluble solids were measured using peeled sections of stem which were crushed to extract clear juice then measured using a digital refractometer. Head density was estimated by weighing each head then immersing in water and measuring the displacement. Additional heads of broccoli were weighed, cooled, packed and transported to Sydney for evaluation of storage and shelf life.

Trial 2 determined the effect of delays in cooling on broccoli quality. Broccoli is usually harvested into half tonne plastic bins in the field. These may be stockpiled in the field before transport to the packing facility. Delays can also occur where the packhouse is remote from the field, or when the cooling capacity cannot cope with a large quantity of harvest product at once.

Similar trials were conducted in Gatton, Qld and Manjimup, WA. In each case broccoli was divided into units for treatment. Each unit included six individually tagged and weighed heads, one head with a temperature data-logger inserted into the broccoli stem, and several extra heads as 'buffers'.

Three separate units were exposed to 1, 4 or 6 hours delay (Gatton) or 4, 8, 10 or 30 hours delay (Manjimup) before being cooled using the farms' hydro-vacuum system. Cartons of chilled broccoli were consolidated, then transported to the postharvest laboratory in Sydney. Transport from Manjimup took 5 days, whereas from Gatton to Sydney was overnight.

Weight loss / gain was determined as well as colour, rots, and overall quality by comparison with visual scales. Broccoli was stored at 7 or 16°C, these being the temperatures corresponding to average temperatures during refrigerated and non-refrigerated retail display (project VG13086). Assessments continued at regular intervals until the heads were no longer consumable.

Trial 3 tested different cooling systems for broccoli. While some growers simply room-cool broccoli, others use hydro-cooling, forced air or even hydro-vacuum cooling systems. While such equipment ads cost, it may cool broccoli faster, potentially impacting retail quality. Again, trials were conducted in Gatton (hydro-cooling, room cooling, hydro-vacuum cooling) and Manjimup (room cooling, hydro-vacuum cooling). As previously, weight gain or loss was measured in six heads per treatment unit, and temperature inside broccoli stems was recorded using temperature data-loggers.

After cooling, the broccoli was consolidated and transported to the Sydney laboratory, with quality and weight loss evaluated as described for trial 2.

Trial 4 evaluated the SmartFresh® In-Box system. SmartFresh® consists of the ethylene antagonist 1-methylcyclopropene (1-MCP). SmartFresh® is widely used to retain storage life and quality of fruit such as apples and pears, and has been demonstrated to be effective at slowing yellowing of broccoli. Although registered for this purpose, it is not used commercially due to the logistical difficulty of applying fumigation treatments during short term storage. The new In-Box system consists of sachets of 1-MCP that can be added to packaged products, making it easier to combine with existing handling and packing procedures. RipeLock liners are recommended for use with In-Box instead of conventional LDPE (low density polyethylene) liners as they have reduced permeability to 1-MCP.

Trials were conducted in Werribee, Victoria as well as Manjimup, WA. As previously, treatment units consisted of six tagged heads, one head with data-logger and non-assessed 'buffer' heads. Treatments were applied as soon as possible after harvest and pre-cooling, or following overnight storage (as would be normal commercial practice). Both trials used 4 x sachets of In-Box per ~8kg broccoli, with the samples packed either in RipeLock or in standard LDPE liners. Broccoli was also packed into styrofoam cartons with ice, again as per normal commercial practice.

All samples were consolidated and transported to the Sydney laboratory. The samples from Werribee were transferred within 24 hours, those from Manjimup took 5 days. The Werribee samples were assessed 1-2 times weekly during storage at 5°C, while those from Manjimup were stored at 7 and 16°C as previously described. In all cases assessments continued until broccoli was no longer edible.

All data was analysed using CoStat statistical software to calculate least significant differences between mean values.

Outputs

Trial results have been provided to both of the project collaborators in Gatton Qld.

The initial results of the SmartFresh® In-Box trials has been presented and discussed with representatives from AgroFresh Pty Ltd.

An article on the initial trials was featured in VegeNotes 53

A second article is in draft form. This will be provided to Vegetables Australia Magazine, detailing the results of the SmartFresh® trials. This will be produced in conjunction with AgroFresh.

vegenotes 53
2016

IN THIS ISSUE:

- A multi-faceted approach to soil-borne disease management

  Hort Innovation R&D project number: VG15010

  Project VG15010 will provide Australian vegetable growers with the tools and solutions to manage the risk of crop losses due to soil-borne diseases in the major vegetable growing regions in Australia.

- Process improvements for preserving peak freshness of broccoli (Stage 2)

  Hort Innovation R&D project number: VG14062

  Project VG14062 is evaluating the cost efficiency of different cooling methods for preserving the peak freshness of broccoli.

A soil-borne disease master class held in September 2015 attracted 25 growers and advisers who heard cutting-edge advice on managing soil-borne disease in a variety of vegetable production systems.

A monitoring, evaluation, reporting and improvement plan will also be developed and utilised during the project.

"With Kym White's detailed economic analyses, we expect to have a more accurate assessment of the value of this project, as well as the chance to communicate the benefits of improved soil-borne disease management options," Dr Rogers said.

Acknowledgements

This project has been funded by Horticulture Innovation Australia Limited using the National Vegetable Levy and funds from the Australian Government.

THE BOTTOM LINE: VG15010

- Project VG15010 will provide Australian vegetable growers with the tools and solutions they need to manage the risk of crop losses due to soil-borne diseases in the major vegetable growing regions in Australia.
- The added research and economic skills mean the AHR/RMCG and NSW DPI will be able to fill the gaps in soil-borne disease management knowledge, which growers and advisers urgently need to minimise financial risks from soil-borne disease.
- New information will be communicated to growers and advisers through the Soil Wealth and ICP extension framework via the established network of demonstration sites and field days, and well as print and electronic media.

Process improvements for preserving peak freshness of broccoli (Stage 2)

Facilitators:

Project VG14062 is being conducted by Dr Jenny Ekman, from Applied Horticultural Research (AHR), with assistance from Dr Gordon Rogers and Emma Winley, also from AHR.

Introduction

When the Australian vegetable industry commissioned a series of studies on consumer vegetable choices in 2013, broccoli was a popular purchase.

But despite its reputation as a tasty, versatile and nutrient-dense "super food", broccoli purchases have remained relatively low, hampered by inconsistency in retail quality and shelf life.

"Nutrition and flavour obviously play a major role in consumers' decision making, but appearance is also extremely important," said Dr Jenny Ekman, from Applied Horticultural Research (AHR).

About the project

Project VG14062 is in the second stage of a research project that is identifying process improvements for preserving peak freshness of broccoli.

Stage one of the project, which was recently completed by Dr Ekman and the AHR team, evaluated retail displays to ascertain whether consumer expectations of broccoli were likely to be met.

"The previous study (VG13083) found that refrigerated retail displays averaged around seven degrees Celsius, while ambient displays were closer to 16 degrees Celsius," Dr Ekman explained.

"However, these averages concealed a huge range of variation and overlap.

"Cold temperatures were no guarantee of quality – some of the highest quality broccoli was purchased from open displays and some of the worst from refrigerated units.

"The results indicated that consumers were likely to be disappointed in broccoli quality at least one shopping trip in four, which is clearly too many."

With phase two of the project, the focus is on finding ways to improve retail quality of broccoli.

"This work has included an evaluation of other supply chains, including iced versus non-iced systems, and initial tests of storage technologies on packed broccoli," Dr Ekman said.

Trials have been conducted on farms at Gatton, Queensland to examine the effect of different cooling methods on broccoli quality and storage life.

The effect of delays in delivering harvested broccoli to the pack house for cooling on quality and storage life was also investigated, along with the effect of harvest time on broccoli quality attributes.

After harvest and cooling, packed crates of broccoli were palletised and transported overnight to Sydney for evaluation of storage and shelf life at seven degrees Celsius and 16 degrees Celsius to replicate commercial practice.

Major findings

Vacuum cooling immediately after harvest and hydrocooling both

retained quality and increased the weight of harvested broccoli.

While part of this initial increase was due to water adhering to the outside of the broccoli, most of the moisture was internalised.

"Broccoli that was held overnight at 16 degrees Celsius before vacuum cooling still had good quality, but weight loss increased," Dr Ekman said.

In general, quality differences during storage and shelf life were subtle, but there was a definite trend to better quality in broccoli that was vacuum cooled immediately after harvest.

All differences in weight were retained through transport and storage, with increased weight reflected in firmer broccoli at retail. Increased weight also means increased profitability for the grower.

In terms of transportation, Dr Ekman said there was some uncertainty among growers about whether broccoli needed to be delivered to the pack house immediately or whether the process could be delayed.

"Logistically, it can be quite difficult to get broccoli from the field to the pack house immediately," she said.

"We found that leaving harvested bins of broccoli in the field rather than immediately transporting them to the packing shed increased weight loss by up to six per cent, which is not a profitable outcome.

"We then compared the cost of different cooling methods. Vacuum cooling is by far the most energy efficient, as nearly all of the energy used cools the broccoli, minimising losses to equipment and the external environment."

Time of harvest also plays a role in broccoli quality.

The greatest gains in weight during cooling were observed in broccoli harvested at 6am, with less increase at 11am and the smallest increase at 4pm. However, broccoli is at its sweetest last thing in the afternoon.

Next steps

Trials are currently underway in Victoria and Western Australia to test the effectiveness of the SmartFresh In-Box Quality System, a tool for fruit quality management that has scope to be used for broccoli.

"Preliminary SmartFresh trials conducted with broccoli have been really promising – in fact, initial storage quality was just as good as broccoli stored with ice," Dr Ekman said.

"But unlike ice, the benefits continue after the broccoli is removed from the box and placed on retail display. Less yellowing at retail means happier consumers and better sales for growers."

THE BOTTOM LINE: VG14062

- Although a hydro-vacuum cooler represents a major up-front investment, this is offset by reduced energy costs, increased saleable weight of product and better quality post-harvest.
- New technologies such as SmartFresh may provide a cost-effective alternative to ice, helping to deliver fresher broccoli to consumers.

Acknowledgements

This project has been funded by Horticulture Innovation Australia Limited using the National Vegetable Levy and funds from the Australian Government.

Photo credits:

VG15010 photos credit: Dr Gordon Rogers and stock images.

VG14062 photos credit: Dr Jenny Ekman, Dr Gordon Rogers and stock images.

Please contact Alexander Nugent at AUSVEG on 03 9882 0277 or email Alexander.Nugent@ausveg.com.au to submit topics for potential inclusion in future editions of vegenotes.

ISSN: 1449 - 1397

vegenotes is produced by AUSVEG Ltd
PO Box 138, Camberwell, Vic, 3124
T: 03 9882 0277 | F: 03 9882 6722

This project has been funded by Horticulture Innovation Australia Limited using the National Vegetable Levy and funds from the Australian Government.

AUSVEG
Horticulture Innovation Australia

Outcomes

Review and energy cost analysis

In California, broccoli is usually field packed into waxed cartons, palletised, then pressure injected with an iced water slurry. This pre-cools the broccoli, as well as leaving behind a solid mass of ice and broccoli inside the cartons. Although energy and transport costs are increased, this method is still used for around 90% of US broccoli, including that exported to countries such as Japan.

In Canada costs are greater, so the ice-slurry method is only used for product that is to be sold to customers in the USA. Other Canadian firms pack in styrofoam plus top icing, or in cartons with liners.

Styrofoam cartons topped with flaked ice are also used in Japan, and for export by countries such as Turkey. In England some producers have moved to cartons with liners, but styrofoam plus ice is still used by some there as well. Other European countries – such as Germany – have moved strongly to recyclable packaging systems. It is not known if styrofoam cartons are still in use, but the costs of disposal of such materials are likely to be significant.

The review of energy costs demonstrated that the energy efficiency of cooling with ice (as in the USA) is extremely low. Vacuum and hydro-vacuum cooling are the standout methods in terms of energy efficiency. This is because approximately 82% of the energy input goes into cooling the product, rather than cooling equipment or being lost to the external environment. Forced air cooling is the next most efficient method. Room cooling is surprisingly inefficient, largely because of the time taken and leakage through doors, floors, etc.

Trial 1

Measurements of head density did not change significantly due to time of harvest (6:00, 11:00 or 16:00). However, soluble solid content in the broccoli stems was significantly higher in the later afternoon than during the day. This is in agreement with previous published results demonstrating that photosynthesis allows broccoli heads to accumulate carbohydrates during the day.

The observed differences in carbohydrates did not affect yellowing, rots or acceptability during subsequent storage at 7 or 16°C. Harvest time did affect weight, however, with those cut early in the morning gaining weight following cooling and transport. In contrast, those harvested at 16:00 lost around 1% weight during this process, with broccoli harvested at 11:00 intermediate. Differences in weight immediately after cooling were retained during storage life, so would have contributed to total yield and, possibly, head firmness.

Trial 2

Cooling broccoli as soon as possible after harvest retained weight and improved quality during simulated retail display. The differences were most significant in broccoli transported through a long supply chain – from Manjimup to Sydney – compared to broccoli that had a relatively short supply chain – from Gatton to Sydney.

Delaying the return of harvested broccoli to the packhouse increased weight loss by up to 8% compared to product that was delivered and cooled immediately. Although broccoli gained 6-7% weight during hydro-vacuum cooling in both trials, broccoli that had suffered increased dehydration did not recover during this process. Differences in weight gain or loss were retained during subsequent transport and storage, confirming that this moisture had been fully absorbed into the broccoli head, and was not merely clinging to the outside. Such weight increases therefore translate into firmer heads during retail display, and improved freshness in the eyes of consumers.

Trial 3

Hydro-vacuum cooling was much faster than room cooling in both cases or the hydro-cooling system that was tested in Gatton. Immediate hydro-vacuum cooling also increased broccoli weight; by 2−3% for broccoli from Gatton, and 6−7% for broccoli from Manjimup. In contrast, broccoli that was room cooled lost 1−2.5% weight during cooling and transport. Increased moisture content directly increases returns to the grower, and is likely to result in improved firmness of broccoli heads at retail.

Although a trend to better quality was observed for hydro-vacuum cooled broccoli, measured differences in quality attributes during shelf life were not significant. However, this may be due to the small quantities of broccoli that were used; cooling would be much slower inside a half tonne bin placed at the back of a cold room than in the plastic crates used in this trial. Previous results indicated that room cooled broccoli can take several days to cool below 5°C – which is very different to the data recorded here.

Trial 4

In both trials the SmartFresh® In-Box treatment reduced yellowing and extended shelf life compared to packing in a liner alone. The results also suggest that this treatment can protect broccoli from fluctuating temperatures, providing a shelf life similar to top icing even given poor cold chain management.

Results were best when the In-Box sachets were combined with the RipeLock liner. This supports the claim that this material is more resistant to diffusion of 1-MCP than standard LDPE film.

While the best results may be gained by treating broccoli immediately after harvest rather than after a 24 hour delay, the data is not conclusive on this point. In the first trial there was no penalty for delaying SmartFresh® treatment for 24 hours, while in the second there were only minor differences. Adding In-Box sachets after overnight storage, rather than immediately after harvest, would be the easiest procedure to fit into existing practices. It seems likely this would still provide effective treatment.

Evaluation and Discussion

The results of these trials confirm that proper cold chain management is essential to maintaining broccoli freshness up until retail. The effects of poor practices at harvest were most easily apparent when broccoli was stored for an extended period and/or subjected to temperature fluctuations within the supply chain.

Although harvest time was not found to affect shelf life in these trials, delays before cooling had a major effect. This was not evident when the heads were first evaluated after packing and transport. However, clear differences appeared during storage, particularly at 7°C.

The significant gains in weight during hydro-cooling and hydro-vacuum cooling are particularly noteworthy. The costs of installing a hydro-vacuum cooler are in the order of $500K to >$1million. Despite proven savings in electricity, this expense appears difficult to justify for a relatively low return product such as broccoli. However, weight increases of up to 7%, which translate into direct increases in profitability, may be another factor to consider.

Also, although we did not find improved shelf life in hydro-vacuum cooled broccoli in these trials, there is much anecdotal evidence that such differences do exist. We may have been more likely to find clear differences in quality had temperatures been higher at harvest. Differences also might have been greater had we been able to compare the hydro-vacuum cooled product with broccoli that was room cooled in whole bins, rather than the small crates of product that were tested in this trial.

While top icing can buffer temperature fluctuations in supply chains, and is expected by many customers, it adds significant costs for producers and is environmentally unsustainable. Previous research by the authors has found negative effects of top icing on broccoli quality following extended storage. Damage included stem splits, stem rots, blackening of the cut leaf bases and rots in the florets. Similar negative effects have been reported in the peer-reviewed literature. However, no negative effects of top icing were found in these trials, even though the ice melted during transport and storage.

Top icing kept broccoli cold during transport from Manjimup to Sydney. In contrast, broccoli packed into lined cardboard cartons was exposed to temperatures over 10°C, and rarely fell below 5°C during an entire week. Despite this, the SmartFresh® treated broccoli had similar quality and shelf life to that of the broccoli packed with ice. The best results were gained using the RipeLock carton liners, and by treating with SmartFresh® as soon as possible after harvest. However, delaying treatment for 24 hours only marginally reduced effectiveness of this treatment, so would still be a useful treatment.

These results are very promising. It is hoped that this data will encourage AgroFresh Pty Ltd to seek to extend the chemical registration that already exists for SmartFresh® treatment of broccoli in order to include the new In-Box delivery system.

Recommendations

Delays in cooling and temperature fluctuations during transport have the potential to greatly reduce broccoli freshness at retail. It seems likely that poor postharvest temperature management is a key factor in the observed variability in retail quality and frequently short storage life after purchase. A Best Practice Guide for broccoli producers, which includes a cost-benefit analysis of different technologies (such as vacuum-cooling vs room cooling, and ice vs lined cartons) could help supply chain members determine the most efficient practices for their businesses, as well as improve outcomes for consumers.

Broccoli absorbed a significant amount of water during hydro-vacuum cooling. This water was internalised, rather than simply sticking to the surface, with the heads retaining this additional moisture content throughout storage life. Not only does this effectively increase yield for the grower, but is also likely to increase firmness of the head during retail – although this has not been tested.

This also suggests that it may be possible to use internalised water as a vehicle for products which help retain broccoli freshness:

- Sanitisers do not appear to be commonly added to the water in hydro-vacuum coolers. Adding a sanitiser, such as calcium hypochlorite or peroxyacetic acid, could help reduce floret and stem rots during subsequent storage.
- Cytokinins are natural plant hormones that promote cell division and growth. Dips in various cytokinins (natural and man-made) at 20°C have been demonstrated to extend broccoli storage life[3, 4]. Adding cytokinins to water during cooling increases internalisation, so could potentially further enhance this effect, and could be investigated.
- It has been reported in the literature that small declines in carbohydrate levels in broccoli florets after harvest are an important trigger for yellowing and senescence. Placing flowers in a mixture of sanitiser and sugars (eg Chrysal®) can increase vase life. Broccoli is also effectively a 'flower' and similar results have been reported[5, 6]. Clearly it is not practical to store broccoli in vase solutions. However, it appears possible that a water containing carbohydrates, applied during cooling, could have some benefits.

The results with the SmartFresh® In-Box system are definitely promising, and could be incorporated into existing harvest and packing procedures. It would also offer growers an alternative to top icing, in terms of protecting broccoli during storage and transport. . Although SmartFresh® itself is registered for use on broccoli, this registration does not include the In-Box delivery system. It is likely that more data is needed to demonstrate efficacy in order to register this application method. It is recommended that the industry work together with AgroFresh Pty Ltd to generate this data and work towards registration

[3] Downs CG, Somerfield SD, Davey MC. 1997. Cytokinin treatment delays senescence but not sucrose loss in harvested broccoli. Postharvest Biol Technol. 11:93-100.

[4] Xu F et al. 2012. Maintaining quality and bioactive compounds of broccoli by combined treatment with 1-methylcyclopropene and 6-benzyaminopurine. J. Sci. Food Ag. 93:1156-1161.

[5] Irving DE, Joyce DC. 1995. Sucrose suppy can increase longevity of broccoli (*Brassica oleracea*) branchlets kept at 22°C. Plant Growth Reg. 17:251-256.

[6] Xu F. et al. 2016. Reducing yellowing and enhancing antioxidant capacity of broccoli in storage by sucrose treatment. Postharvest Biol. Technol. 112: 39-45.

of this technology for use with broccoli.

Scientific Refereed Publications

None to report

Intellectual Property/Commercialisation

No commercial IP generated

Acknowledgements

The project team would like to acknowledge the invaluable assistance of the firms and individuals that have generously assisted with this project, and without whose help this would not have been possible.

AgroFresh – Hannah James, Peter Vedeniapine

Barden Produce – Clem Hodgman

Fresh Select – Carolyn Thomas

Koala Farms – Anthony Staatz

Qualipac – Troy Qualischevski

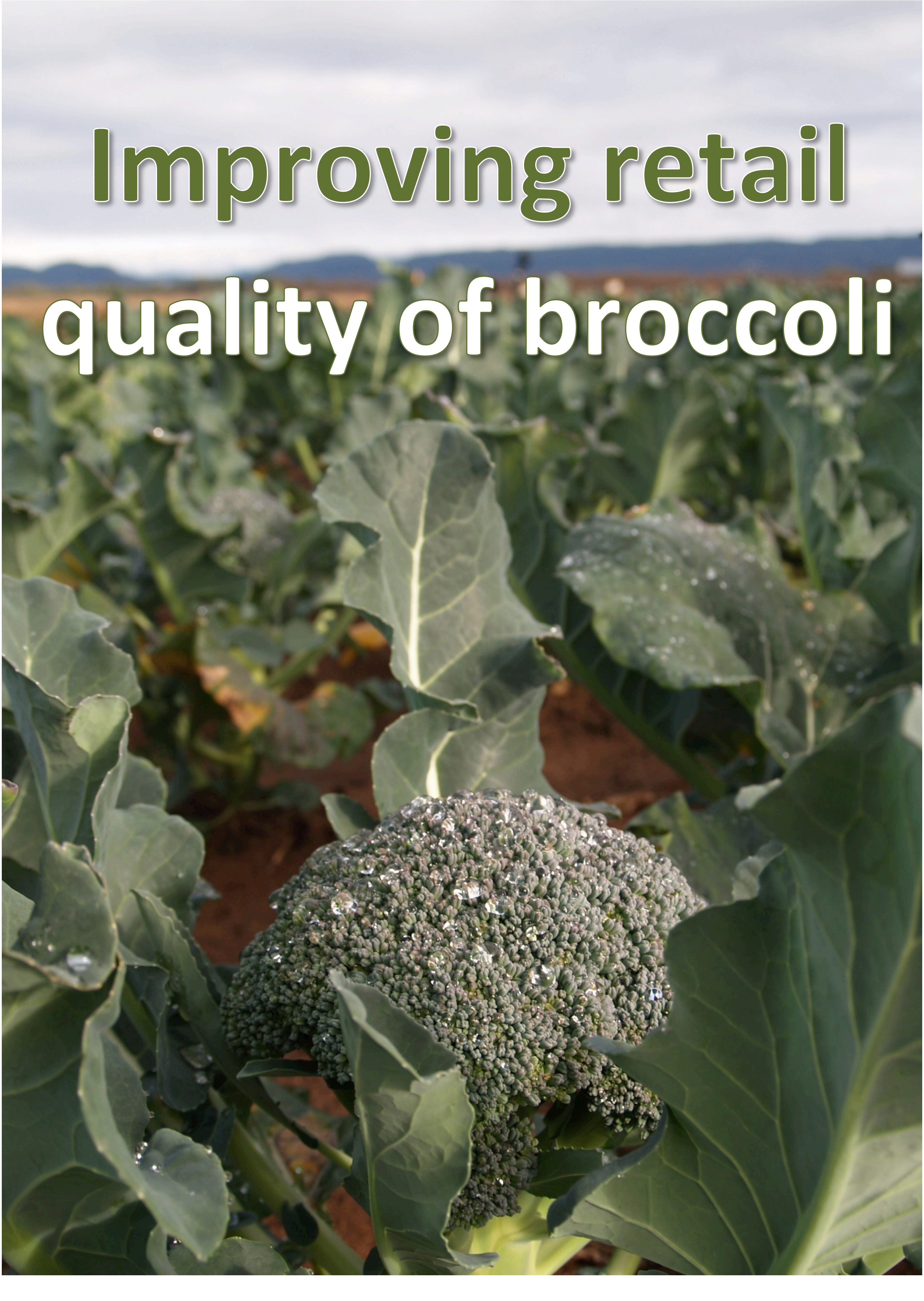
SG AgHort Consulting – Stuart Grigg

Twin Lakes Farm – Brad Ipsen

Appendices

A full description of all methods, materials, results and conclusions arising from the research is appended to this report.

Improving retail quality of broccoli



Contents

Report by Dr Jenny Ekman,

Applied Horticultural Research

6th May 2016

1. Broccoli cooling and packing around the world

1.1.1. Japan

Broccoli can be grown year-round in Japan, with production moving from the north during summer and to the south in winter. While there is a lot of geographic diversity in broccoli production, major growing areas include Hokkaido (summer), Aichi (spring) and Saitama (winter). Many growers do not have irrigation, but rely on rainfall to produce crops.

Figure 1. Japanese farmer harvesting broccoli into crates and broccoli in a Tokyo supermarket.

At harvest, broccoli stems are left relatively long at 120–150mm. This distinguishes locally grown broccoli from imported product, and may help protect it from damage due to the presence of enclosing leaves. This also means the stems can be re-trimmed in-store, which enhances their fresh appearance.

Warfield et al[1] found that Dole (which owns five broccoli production farms in Japan) hydrocools broccoli. The heads are immersed in 2°C water for 20 minutes. They are then placed in stackable plastic crates and stored overnight at 0–1°C.

After thorough cooling, the broccoli is trimmed and packed into styrofoam cartons topped with flaked ice. They are then transported by either road or rail to the wholesale markets. Rail transport is not refrigerated, so dry ice may be placed on top of the palletised cartons to help keep them cool. Road transport is set at 0–2°C.

1.1.2. United States

Broccoli is planted year-round in California, which produces nearly 90% of all broccoli grown in the US. The major Californian season is from October to December. Arizona also produces broccoli, mainly during winter[2].

[1] Warfield B, et al. 2014. Market analysis and strategy: Broccoli to Japan. HIA Final Report VG13048.
[2] Naeve L. 2015. Broccoli. www.agmrc.org/commodities-products/vegetables/broccoli/

Most Californian producers pack into 10kg waxed cardboard cartons in the field. These are palletised and returned to the pack house for cooling. Broccoli may be cooled / pre-cooled using a forced air or hydrocooling system, or sent directly to the ice injection system. It is interesting to note that although hydro-vacuum coolers are commonly used on vegetable farms for lettuce, babyleaf and other crops, there are no reports of them being used for broccoli.

Ice injection or liquid-icing systems produce a super-cooled slurry of water and finely crushed ice. This is pumped under pressure through the carton vents, completely filling each carton. The chilled water in the slurry helps to further cool the broccoli, while the ice is carried into all the voids through the package, bringing it into closer contact with the product than is possible with top icing.

Automated pallet icing systems can both cool and ice a whole pallet at once. The whole enclosure is filled with a slurry of water and ice (Figure 2). These systems are expensive to purchase, but require only a single operator to manage.

It has been reported that some users of such systems add salt to the water so that they can lower the temperatures of the slurry below 0°C, thereby cooling the broccoli faster. Adding 8kg of salt to 100L of water reduces the point at which the water freezes from 0°C to -2.8°C. This does not result in significantly faster cooling, but can dehydrate and/or cause freezing damage to the broccoli. The practice is therefore generally discouraged[3].

The lack of air space inside the ice-filled carton slows down the speed at which the ice melts. However, ice still inevitably melts during storage and transport, resulting in wet floors, wet product and wet transport vehicles. Personal experience of retail cold rooms in the US suggests that any cold rooms used for storing vegetables are permanently wet.

[3] Boyette MD, Estes EA. 1992, Crushed and liquid ice cooling. North Carolina Extension Service Publication AG-414-5

Figure 2. Broccoli icing in California using an ice slurry injection system (top). The result is a carton entirely filled with crushed ice and broccoli (bottom).

1.1.3. Canada

Most Canadian broccoli producers do not use ice injection systems because of cost. There is also concern about the resulting mess of melt water that poses a significant issue for worker health and safety. According to Prof. Peter Toivonen (Agriculture and Agri-Food Canada) only one company in Canada uses an ice injection system, and that is because they re-export to the USA, where their customers expect broccoli to be packed this way.

During the off-season, the company purchases broccoli in California, forced-air cools it, transports it to Quebec, then injection-ices it for supply to customers in Chicago, Boston, etc. As their freight costs are based on weight, this represents a major saving.

Most Canadian producers use hydrocooling or humidified forced-air systems. The traditional method of packing pre-cooled broccoli involved styrofoam containers with top icing. However, as in Australia, there is a move to cartons with liners, which are usually perforated LDPE. There is a sense that ice is only suitable for local distribution, again due to transport costs.

1.1.4. Asia

The process used to cool and pack broccoli in Asia ranges from no cooling, and packed into cardboard boxes, to hydro-vacuum cooling and packed into styrofoam boxes with top icing. Larger Chinese producers use styrofoam and top icing.

1.1.5. Europe

The European Union introduced a packaging and waste directive for all member states in 1994. This policy requires that the cost of recycling or disposal is split between suppliers, manufacturers and users. The difficulty of recycling polystyrene strongly discourages its use in many European countries.

Figure 3. Harvesting broccoli at Oakley Farm, UK, and the finished product from a UK farm.

Some UK producers still pack into styrofoam with top icing, however. Staples Farm, a major vegetable producer in the UK, packs broccoli into 4.5kg polystyrene boxes with 1kg of flaked ice. Other growers appear to be moving to cardboard-plus-liner systems, however, judging from the image shown in Figure 3.

Moreover, much of the product imported into the UK is shipped this way. For example, Egypt exports broccoli by sea and air to the UK during the northern winter. Exports are in 8kg styrofoam boxes with top icing.

Figure 4. Broccoli packed for export from Egypt to the UK by Fruit Link Co.

2. Effect of harvest time on broccoli quality attributes

2.1. Introduction

Broccoli is an immature flower head, and is developing rapidly while attached to the plant. During the day the broccoli plant photosynthesizes, using energy from the sun to lay down storage reserves of carbohydrates such as starch, lipids, sucrose and glucose.

The metabolic processes that allow the plant to grow, develop and function as a living entity are powered through respiration. Respiration is the process by which sugars are oxidised, producing CO_2 and energy. This metabolic activity does not stop when the sun sets, so the plant must draw down on reserves during the night.

The result is diurnal fluctuations in the level of storage carbohydrates, which accumulate during the day but may be re-mobilised by night[4].

Both of these changes may have implications for broccoli quality. Broccoli heads contain few carbohydrate reserves relative to their high metabolic rate[5]. Even a very small decline in sugars in the florets is thought to help trigger the rapid yellowing that occurs in harvested broccoli under ambient conditions[6].

Carbohydrate reserves are likely to be greatest at sunset and lowest at sunrise. Research has shown that broccoli harvested at sunset had higher levels of starch than those harvested at sunrise, with heads harvested during the day being at intermediate level. After several days of storage, the broccoli harvested late in the day contained higher total soluble sugars and had retained its green colour better than those harvested early. In this case the researchers suggest that scheduling harvest late in the day, instead of, as is traditional – in the early morning – could improve broccoli storage life[7].

These results are supported by subsequent research showing that chlorophyll degrading genes are expressed less in broccoli harvested late in the day[8], but also that enzymes involved in sugar metabolism increase[9].

[4] Sicher RC, Kremer DF, Harris WG. 1984. Diurnal carbohydrate metabolism of barley primary leaves. Plant Physiol. 76:165-169.

[5] King GA, Morris SC. 1994. Physiological changes of broccoli during early postharvest senescence and through the pre-harvest-postharvest continuum. J. Amer Soc. Hort. Sci. 119: 270-275.

[6] Irving DE, Joyce DC. 1995. Sucrose supply can increase longevity of broccoli (*Brassica oleracea*) branchlets kept at 22°C. Plant Growth Reg. 17:251-256.

[7] Hasperue JH, Chaves AR, Martinez GA. 2011. End of day harvest delays postharvest senescence of broccoli florets. Postharvest Biol. Technol. 59: 64-70.

[8] Hasperue JH et al. 2013. Time of day at harvest affects the expression of chlorophyll degrading genes during postharvest storage of broccoli. Postharvest Biol. Technol. 82: 22-27.

Along with changes in carbohydrate content, there are differences between day and night in moisture content. During the day the plant stomata are most likely to be open, as the plant turns CO_2 molecules from the air into usable carbohydrates. This allows moisture to escape from the plant leaves. If the rate of moisture loss is faster then the rate at which moisture can be drawn from the soil, the leaves will become limp. At night, the stomata are likely to close and temperatures drop, allowing the plant tissues to fully re-hydrate.

Workers have reported that broccoli heads feel heavier in the morning – when fully hydrated – than later in the afternoon. If this is in fact the case, there could be significant differences in yield, depending on the time of day that broccoli is harvested, especially under warm, sunny conditions.

It therefore seems possible that while head weight is maximised during the early morning, when harvest traditionally occurs, carbohydrate levels are maximised in the late afternoon. Trials were therefore conducted to examine broccoli quality attributes and storage life when harvested at sunrise, midday, and sunset.

2.2. Method

2.2.1. Harvest time

Broccoli was harvested from fields in Gatton (Lockyer Valley of South East Queensland) at 6am, 11am and 4pm on 2 September, 2015. Each harvest consisted of three crates of broccoli, each crate being cut from a different part of the field. Six heads of broccoli were tagged and weighed from each crate, then all of the heads were hydro-vacuum cooled to below 10°C. Total time from harvest to cooling was approximately two hours. Cooling rates were recorded using i-button temperature data-loggers inserted into the centre of the broccoli stems.

All crates were transported overnight to Sydney for shelf-life assessment. On arrival, heads were reweighed and assessed for colour and quality. They were then allocated to storage at either 7°C or 16°C. These temperatures were selected because they represent the average display temperatures for broccoli recorded at retail stores (refrigerated and unrefrigerated display units).

Broccoli stored at 16°C was assessed every 1–2 days, while those at 7°C was assessed every 3–4 days. At each assessment heads were individually weighed and evaluated against a pictorial grading scale for colour, overall appeal, presence of stem rots and floret rots. Each attribute was allocated a grade from 1 to 5, where 1 = best and 5 = worst. Broccoli samples were kept until they were considered no longer marketable or edible.

---

[9] Hasperue JH et al. 2014. Effect of time of day for harvest and postharvest treatments on the sugar metabolism of broccoli (*Brassica oleracea* var. *italica*). Ag Food Sci. 23:48-59.

2.2.2. Stem sugars and density

At each harvest time, 20 additional heads of broccoli were cut for estimation of stem soluble solid content and density.

To estimate soluble solids, a small section of the inner stem was cut from 6cm below the lowest florets on 10 individual heads of apparently equal size and maturity. The section was squeezed using a garlic press and the clear extracted juice was dripped onto a digital refractometer (Hanna Instruments HI 96801).

Density was estimated using 10 individual heads of apparently equal size and maturity. The heads were weighed then carefully dipped into a full container of water, which had been placed inside a larger bowl. The volume of water displaced by the head was then measured volumetrically. Density was calculated by dividing weight by volume of the broccoli head.

2.3. Results

2.3.1. Harvest time

All of the broccoli heads increased in weight after cooling due to water from the hydro-vacuum cooler being absorbed into or remaining on the heads. This gain in weight was greatest in the broccoli harvested at sunrise, and least later in the day, with broccoli harvested at midday as intermediate (Figure 5).

It had been expected that broccoli harvested during the heat of the late afternoon would be less turgid than that harvested at dawn (6am), when plants were expected to be fully hydrated. The combination of warmer product, and increased internal osmotic potential of product harvested late in the day, had been expected to drive moisture uptake during cooling.

In this trial, the opposite occurred, with water uptake greatest in the earliest harvested heads. Broccoli harvested at 6am consistently gained 2% more weight than those harvested at 4pm. Differences at harvest were retained during storage and shelf life, demonstrating that weight gain was due to internalisation of water, not water simply adhering to the outside of the heads.

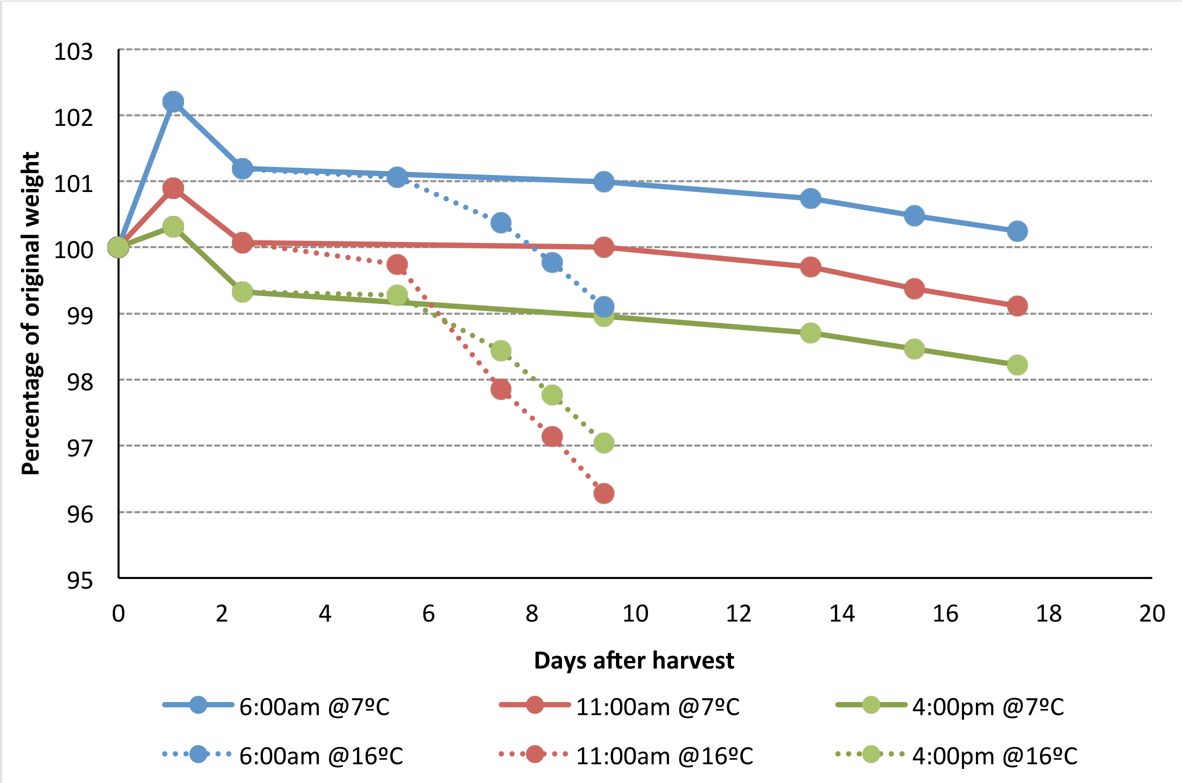


Figure 5. Weight gain/loss of broccoli harvested at three times of day; 6am, 11am and 4pm, and cooled in a hydro-vacuum cooler before storage at 7°C or 16°C.

Harvest time had no effect on the rate of yellowing, overall acceptability during storage, or the incidence of head rots ($p>0.05$). There was a trend towards a lower incidence of stem rots in broccoli harvested at 4pm when stored at either 7°C or 16°C. However, this was not significant at the 5% confidence level.

2.3.2. Stem sugars and head density

Broccoli head density did not differ between harvest times, at least using the measurement method that we had devised. It had been hypothesised that loss of turgor during the heat of the day may reduce density. However, this was not observed in the current trial. The results therefore suggest there would be no difference in total yield from a field harvested in the early morning to one harvested in the late afternoon (Table 1).

As predicted from the available literature, soluble solids were higher in the stem in the late afternoon than they were in the morning (Table 1). Photosynthesis during the day would be expected to increase accumulation of carbohydrates in the broccoli stem. During the night these will be depleted due to the rapid respiration of the florets. The results are consistent with this effect. However, it is also possible that the observed apparent increases are due to reduced hydration of the stem tissues during the heat of the afternoon.

Table 1. Effect of harvest time of day on broccoli head density and soluble sugars. Letters indicate mean values that are statistically significant ($p<0.05$).

Harvest time	Head density (g/cm^3)	Soluble sugars (%)
6 am	0.92*	5.19 a
11 am	0.93*	5.11 a
4 pm	0.92*	5.86 b

*Means not statistically significant at $p<0.05$

2.4. Conclusions

Increased weight of up to 2% in broccoli harvested at 6am compared to a 4pm harvest could be commercially significant. At a conservative farm-gate price of $2500/tonne, 2% extra weight results in an extra $50/tonne direct profit to the grower. Further trials are required to determine why broccoli harvested earlier in the day increases in weight more than that harvested later in the day during vacuum cooling.

The reported retention of green colour in broccoli harvested at sunset compared to that harvested at dawn was not observed in this trial. In the experiments reported in the literature, broccoli was not pre-cooled, but simply placed at 20°C for observations. In our case, we attempted to mimic what could happen in an actual supply chain, where broccoli is cooled, transported, then placed on retail display.

Senescence processes at 20°C may be different to those at 16°C, especially when the lower shelf life temperature follows a period of cold storage, and are certainly different to those at 7°C. It is possible that the period of storage and transport in our trial eliminated any advantage of the late-harvested broccoli over those harvested at dawn, reducing all of the heads to a similar level of base carbohydrate supply.

3. Effect of delays in cooling on broccoli freshness

3.1. Introduction

Delays in cooling may occur where harvested broccoli is transported significant distances to the pack house; where the pack house is running above their cooling capacity, and cannot cool the broccoli immediately; or where the bins of harvested broccoli are stockpiled in the field before transporting to a nearby pack house. Brennan and Shewfelt[10] found that retail quality of broccoli could be negatively impacted by as little as three hours delay in cooling after harvest.

Trials were therefore conducted to examine the effect of delays in transporting broccoli to the pack house on storage and shelf life. Trials were conducted in Gatton, Qld and Manjimup, WA. In this way we were able to examine the effect of cooling delay on broccoli from very different production areas, which were then handled through very different supply chains.

3.2. Method

3.2.1. Gatton trial setup

Nine crates of broccoli were harvested from fields near Gatton at approximately 9am on 3 September, 2015 and divided into nine separate treatment units. A temperature logger (i-buttons, Maxim Int.) was inserted into the thickest part of the stem of one head of broccoli from each unit. The stem was then taped up and head marked with flagging tape for later retrieval. A further six randomly selected heads from each treatment unit were tagged, weighed, and the weight recorded. The remaining heads in each unit were simply used as 'fillers'. Before cooling, crates of broccoli were covered and held outside in ambient conditions.

Three different cooling-delay treatments were applied:

1. Minimum delay – 1 hour from harvest
2. Moderate delay − 4 hours from harvest
3. Lengthy delay − 6 hours from harvest

At the designated time after harvest, crates were placed inside the hydro-vacuum cooler. On removal they were individually reweighed, then stored in the cool room at approximately 2°C.

[10] Brennan PS, Shewfelt RL. 1988. Effect of cooling delay at harvest on broccoli quality during postharvest storage. J. Food Qual. 12:13-22.

Six heads of broccoli were tagged and weighed in each crate before and after cooling inside a hydro vacuum cooler. After cooling, product was held in cold storage and then shipped to Sydney for shelf life assessment at either 7°C or 16°C. Broccoli was regularly weighed and assessed for head colour, overall appeal, presence of stem rots and head rots using a subjective scale of 1 to 5 (1 = best, 5 = worst).

All of the units were then consolidated on a single pallet and shipped overnight to Sydney. On arrival at the Sydney depot at Kemps Creek, the broccoli samples were collected and transferred to the postharvest laboratory at the University of Western Sydney at Hawkesbury for assessment and storage.

3.2.2. Manjimup trial setup

Twelve crates of broccoli were harvested from fields near Manjimup at 8am on 7 March, 2016. The field was more than 30km from the packing facility and accessed by dirt roads only, so it took two hours before the first batches of harvested product were brought to the packing shed.

Figure 6. Bin of broccoli freshly harvested in Manjimup.

The broccoli was then randomly allocated to four different cooling delay treatments, each with three replicates (total = 12 units). As previously, each unit consisted of one head with a data-logger inserted into the centre of the stem, six heads which were tagged and weighed, and a number of additional heads as buffers. Before cooling, crates of broccoli were covered and held outside in ambient conditions.

Four different cooling-delay treatments were applied:

1. Minimum delay – 4 hours after harvest
2. Moderate delay – 8 hours after harvest
3. Lengthy delay – 10.5 hours after harvest
4. Overnight delay – 30 hours after harvest

At the designated time after harvest, crates were placed inside the Barden Produce hydro-vacuum cooler. On removal they were individually reweighed, then stored in the cool room at approximately 2°C. All treatments were palletised and sent on 9 March by truck to Sydney, with transfers in both Perth and Adelaide.

The consignment was collected in Sydney following its arrival on 14 March. The cartons of broccoli were then transferred to the postharvest laboratory at University of Western Sydney, Hawkesbury for shelf-life assessment.

3.2.3. Shelf-life assessment

On arrival at the postharvest laboratory all heads were weighed and assessed for quality attributes including:

- Colour (by comparison with photographic scale)
- Presence of rots in florets or stem
- Overall marketability / acceptability

The units were then divided into two – half of the heads were stored at 7°C and the remainder at 16°C. These temperatures were used as they correspond to average retail temperatures in refrigerated and non-refrigerated display units. Storage conditions were monitored with temperature and relative humidity data-loggers.

Quality attributes and weight of broccoli heads at 16°C were evaluated daily, while heads at 7°C were evaluated twice weekly. Assessments continued until the broccoli was no longer considered marketable.

3.3. Results

3.3.1. Gatton trial results

Leaving broccoli in the field for up to six hours had minor effects on broccoli colour, acceptability, stem rots and head rots. However, delayed delivery of harvested broccoli to the pack house for cooling increased weight loss by 5–6% (Figure 7). This difference remained throughout storage and shelf life, and is likely to be reflected in firmness and turgidity at retail.

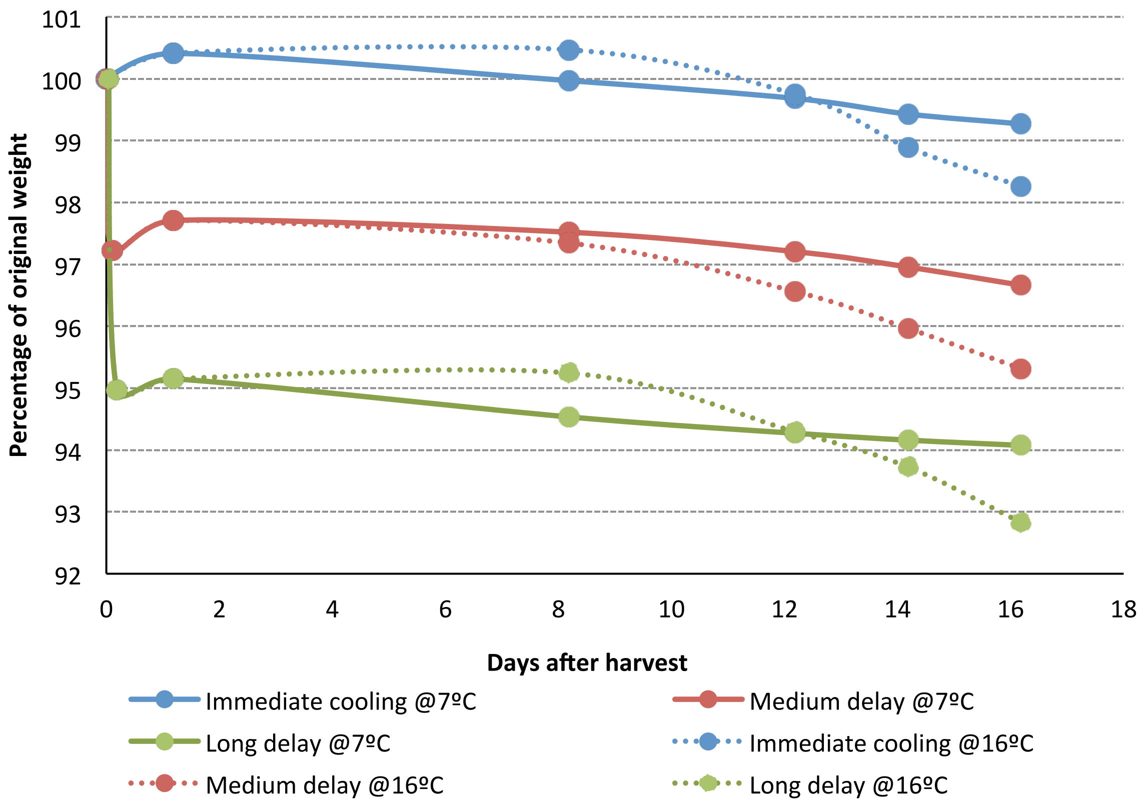


Figure 7. Weight gain/loss of broccoli cooled in a hydro vacuum cooler at delays after harvest of 1 hour (immediate), 4 hours (medium) and 6 hours (long) before storage at 7°C or 16 °C.

Broccoli gained weight during cooling due to the hydration of the broccoli heads as well as water remaining on the heads. Once the broccoli was delivered to the postharvest laboratory, the heads were superficially dry; differences observed after this time are entirely due to the moisture content of the broccoli.

3.3.2. Manjimup trial results

In the Manjimup trial, there were major differences between broccoli subjected to different periods of delay before cooling. This was despite mild weather (approx. 20°C ambient) at harvest.

Weight loss increased with delay before cooling. While broccoli regained weight (approx. 5–6%) during the vacuum cooling process, it did not recover from its previous dehydration (Figure 8). As a result, broccoli harvested within four hours of harvest was 7% heavier immediately after cooling than that which had been subjected to an extended delay.

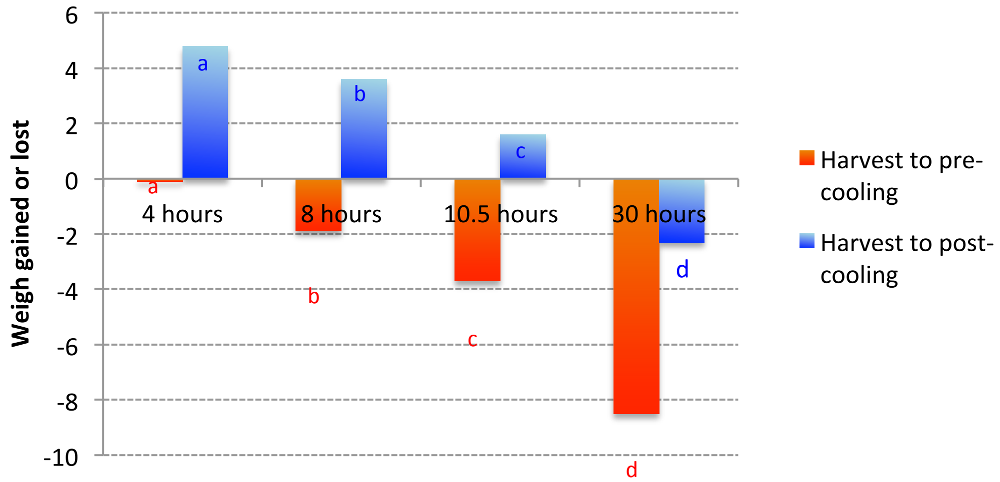


Figure 8. Weight gained or lost between the time broccoli was harvested and the time it was placed in the hydro-vacuum cooler, and the time broccoli was harvested and the time it was removed from the hydro-vacuum cooler. Letters indicate means that are significantly different (n=18).

These differences in weight loss may be part of the reason there were also significant differences in quality of broccoli subjected to different delays before cooling (Table 2). Delaying cooling of broccoli increased yellowing during simulated retail display and reduced appearance and, therefore, saleable life (Figure 9). Even simply doubling the time until cooling from the minimum four hours to eight hours reduced retail quality.

Table 2 - Effect of delay before cooling on colour, appearance and rot development during simulated retail display at 16 or 7°C. Subjective assessment made using a scale of 1-5, where 1=excellent and 5=very poor Letters indicate means that are significantly different (p<0.05).

Delay before cooling	Stored at 16°C for 1 day			Stored at 7°C for 4 days		
	Colour	Quality	Rots	Colour	Quality	Rots
4 hours	2.1 a	2.1 a	1.8 a	2.0 a	2.1 a	1.4 ab
8 hours	2.2 a	2.0 a	1.6 a	2.6 b	2.6 a	1.2 b
10.5 hours	1.9 a	2.0 a	1.2 a	3.1 c	3.3 b	2.1 a
30 hours	3.3 b	3.3 b	1.9 a	3.9 d	3.7 b	1.6 ab

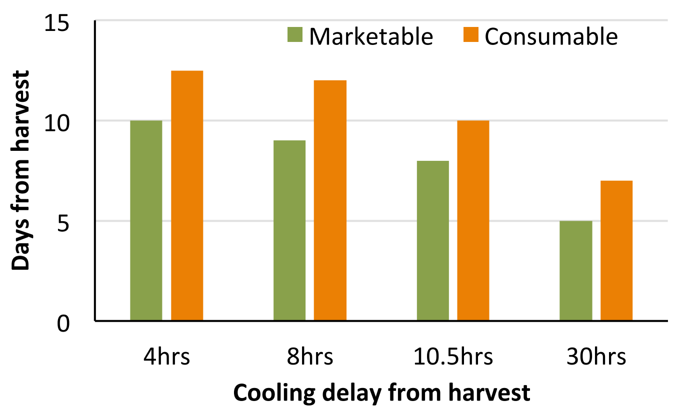


Figure 9 - Days that broccoli remained marketable (quality = good) and days that broccoli remained consumable (quality = OK) following harvest, 4 – 30 hours delay before hydro-vacuum cooling, then transport to Sydney and simulated retail display at 7C.

3.4. Conclusions

Cooling broccoli as soon as possible after harvest retained weight and improved quality during simulated retail display. The differences were most significant in broccoli transported through a long supply chain – from Manjimup to Sydney – compared to broccoli that had a relatively short supply chain – from Gatton to Sydney. They were also more obvious when broccoli was held at 7°C, as could occur during refrigerated retail display, or indeed during storage in a retail store coolroom. At higher temperatures broccoli deteriorated quickly, so fewer differences were observed.

Delaying the return of harvested broccoli to the pack house increased weight loss by up to 8% compared to product that was delivered and cooled immediately. Although broccoli gained 6–7% weight during hydro-vacuum cooling in both trials, broccoli that had suffered increased dehydration did not recover during this process. Differences in weight gain or loss were retained during subsequent transport and storage, confirming that this moisture had been fully absorbed into the broccoli head, and was not merely clinging to the outside. Such weight increases therefore translate into firmer heads during retail display, and improved freshness in the eyes of consumers.

This difference in weight is also commercially significant. At a (conservative) farm-gate price of $2,500/tonne, 5% extra weight results in an extra $125 direct profit to the grower. This suggests that growers need to prioritise the return of harvested broccoli to the pack house in order to maximise yield. Delays in cooling once the broccoli is shaded and protected from the wind have less effect.

4. Effect of cooling method on broccoli freshness

4.1. Introduction

Much of the work on maintaining broccoli quality during storage has focused on the importance of storage temperature[11] as well as technologies such as packaging films[12]. Recent work has examined novel treatments such as exposure to light (UV, LEDs)[13, 14], dips in various compounds[15], and even heat treatments[16].

However, the first treatment that occurs after broccoli is harvested is cooling. The cooling method used, and the speed with which broccoli is brought below 5°C, are likely to have major impacts on storage life and quality.

Several researchers have examined the effect of cooling method on broccoli storage life. For example, hydrocooling reduced broccoli temperature from 22°C to 6°C in only 12 minutes, compared to at least 1.5 hours with top icing and >4 hours with room cooling. The hydro-cooled broccoli subsequently had improved firmness and stayed green for longer compared to the room-cooled product[17]. Forced air (pressure) cooling can also reduce broccoli temperature relatively quickly compared to ice cooling or room cooling[18].

The fastest method of cooling is generally vacuum, or hydro-vacuum cooling. Vacuum cooling can rapidly remove field heat by evaporating water directly from the product. Alibas and Koksal[19] compared forced air cooling to vacuum cooling and hydrocooling for cauliflower. Vacuum cooling was the fastest and most energy-efficient cooling method, and also resulted in the firmest heads even though the system used resulted in increased weight

---

[11] Klieber A, Wills RBH. 1991. Optimisation of storage conditions for 'Shogun' broccoli. Scientia hort. 47:201-208.

[12] DeEll JR, Toivonen PMA. 2000. Chlorophyll fluorescence as a nondestructive indicator of broccoli quality during storage in modified atmosphere packaging. HortScience. 35:256-259.

[13] Hasperue JH et al. 2016. Continuous white-blue LED light exposure delays postharvest senescence of broccoli. LWT- Food Sci. Tech. 65: 495-502.

[14] Rybarczyk-Plonska A. et al. 2014. Vitamin C in broccoli flower buds as affected by postharvest light, UV-B irradiation and temperature. Postharvest Biol. Technol. 98:82-89.

[15] DeEll JR, Toivonen PMA, Vigneault C. 2001. Postharvest dips to control black speck and scar discolouration in stored broccoli. J. Food Qual. 24:575-584.

[16] Forney CF, Jordan MA. 1998. Induction of volatile compounds in broccoli by postharvest hot water dips. J. Ag. Food Chem. 46:5295-5301.

[17] Gillies SL. Toivonen PMA. 1995. Cooling method influences the postharvest quality of broccoli. HortSci. 30:313-315.

[18] Yan L, Liu S. 2010. Effect of different pre-cooling, packaging and cold storage treatments on quality of broccoli. Acta Hort. 934:1149-1156.

[19] Alibas I, Koksal N. 2014. Forced-air, vacuum, and hydro precooling of cauliflower (*Brassica oleracea* L. var. *botrytis* cv Freemont): part 1. Determination of precooling parameters. Food Sci. Technol. 34: 730-737.

loss during cooling. Weight loss during vacuum cooling can be reduced or eliminated using modern hydro-vacuum systems that spray water onto the product during de-pressurisation[20].

While hydro-vacuum coolers are fast and energy efficient, they are also expensive. However, this cost may be justified in part if broccoli storage life and quality are improved using this technology compared to other cooling methods.

The following trials were conducted to examine how cooling method, and to a certain extent cooling delay, affected broccoli quality during simulated retail display. Trials were conducted in Gatton, Qld and Manjimup, WA. In this way we were able to examine the effect of cooling method on broccoli from completely different production areas, which were then handled through very different supply chains.

4.2. Method

4.2.1. Gatton trial setup

Broccoli was freshly harvested at Gatton at approximately 10am on 26 August, 2015. The weather was warm and sunny, so temperature of the harvested broccoli was 20–23°C by the time it was returned to the packing shed.

Figure 10. Broccoli harvest in Gatton.

Temperature loggers (i-buttons, Maxim Int.), were inserted into the thickest part of the stem of 15 heads of broccoli. These were taped up and marked with flagging tape for later

[20] Ding T. et al. 2014. Simulation technique for optimal design of vacuum cooling on broccoli by simulated annealing technique. Int. J. Agric. Biol. Eng. 7:111-115.

retrieval. Units were collated which consisted of one head with a logger and six heads, which were weighed and weight recorded. Treatments were:

1. Vacuum cooling – ASAP
2. Hydrocooling – ASAP
3. Room cooling – immediate start
4. Vacuum cooling – delayed for 24 hours
5. Hydrocooling – delayed for 24 hours

Cartons were placed in returnable plastic crates along with 'filler' heads so as to approximate commercial packing procedures. Room cooling was conducted by simply placing the packed crate inside the cool room. Vacuum cooling was done using the Barden Produce hydro-vacuum cooler. Broccoli was hydrocooled using a static bin system at the nearby Qualipac packing facility (Figure 11).

Figure 11. Hydrocooling at Qualipac and room cooling of broccoli at Barden Produce, Gatton.

After treatment, all of the units were reweighed then consolidated on a single pallet and shipped overnight to Sydney.

On arrival at the Sydney depot at Kemps Creek, the cartons of broccoli were collected and transferred to the postharvest laboratory at the University of Western Sydney at Hawkesbury.

4.2.2. Manjimup trial setup

Nine crates of broccoli were harvested from fields near Manjimup at 11am on 8 March, 2016. They were returned to the packing facility and randomly allocated to three different cooling methods, each with three replicates (total = 9 units). As previously, each unit consisted of one head with a data-logger inserted into the centre of the stem, six heads which were tagged and weighed, and a number of additional heads as buffers. Treatments were:

1. Hydro-vacuum cooling – crates placed inside a commercial bin of broccoli
2. Room cooling – crates placed inside the cool room
3. Hydro-vacuum cooling inside LDPE liner – crates placed inside a commercial bin of broccoli

Cooling rates were measured using Hobo UX100 temperature + RH data-loggers placed inside the crates as well as the i-button temperature loggers inside the broccoli heads.

After cooling, hydro-vacuum cooling treatments were held in cold storage along with the room cooling treatment. All treatments were palletised and sent on 9 March by truck to Sydney, with transfers in both Perth and Adelaide.

The consignment was collected in Sydney following arrival on 14 March. The cartons of broccoli were then transferred to the postharvest laboratory at University of Western Sydney, Hawkesbury for shelf-life assessment.

4.2.3. Shelf-life assessment

On arrival at the postharvest laboratory all heads were weighed and assessed for quality attributes including:

- Colour (by comparison with photographic scale)
- Presence of rots in florets or stem
- Overall marketability / acceptability

The units were then divided into two – half of the heads were stored at 7°C and the remainder at 16°C. These temperatures were used as they correspond to average retail temperatures in refrigerated and non-refrigerated display units. Storage conditions were monitored with temperature and relative humidity data-loggers.

Quality attributes and weight of broccoli heads at 16°C were evaluated daily, while heads at 7°C were evaluated twice weekly. Assessments continued until the broccoli was no longer considered marketable.

4.3. Results

4.3.1. Gatton trial results

The hydrocooling system that was used in this trial did not cool the broccoli any faster than simply placing it in a cold room (Figure 12). Moreover, because of the time taken to transfer the broccoli from the hydrocooler back into the cold room, this broccoli stayed warmer for longer.

As it was not possible to room-cool broccoli as a full half-tonne bin, this is not fully representative of what would happen with a commercial quantity. Broccoli in the centre of a bin would cool much more slowly than was observed in this trial, where the product was packed loosely into plastic crates.

The vacuum cooler was clearly the fastest method of cooling, reducing temperature by around 10°C within 20 minutes (Figure 12).

However, it is noted that the broccoli was removed from the vacuum cooler somewhat prematurely, given that the stated aim was to cool below 5°C; during times of high demand on the equipment, shorter cooling cycles may be used. Although this may appear less than optimal, it may be a better strategy to cool all harvested product below 10°C as quickly as possible than to fully cool some product while leaving other bins waiting on the dock.

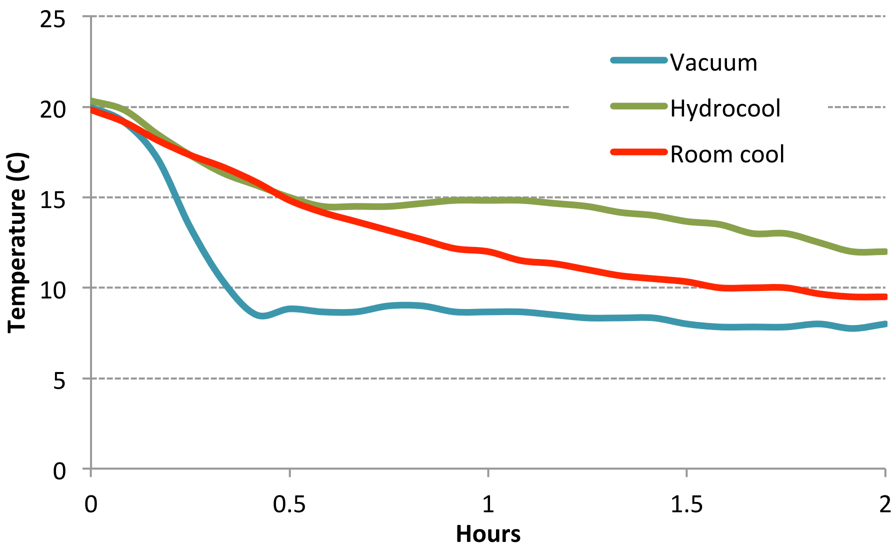


Figure 12. Cooling rates using a hydro-vacuum cooler, hydrocooler and room cooling.

Immediate hydro-vacuum cooling and either immediate or delayed hydrocooling both increased the weight of the broccoli relative to its weight at harvest (Figure 13). While some of this effect was due to water adhering to the product surface, these differences remained even after the broccoli had thoroughly dried. This indicates that much of this gain was due to internalised moisture.

Differences in weight gain or loss before and during cooling were retained during transport and storage.

Broccoli that was vacuum cooled immediately after harvest retained slightly higher overall appeal compared to all other treatments. However, this difference only became evident after 3 weeks storage at 7°C; at shorter storage times there were no differences between the treatments.

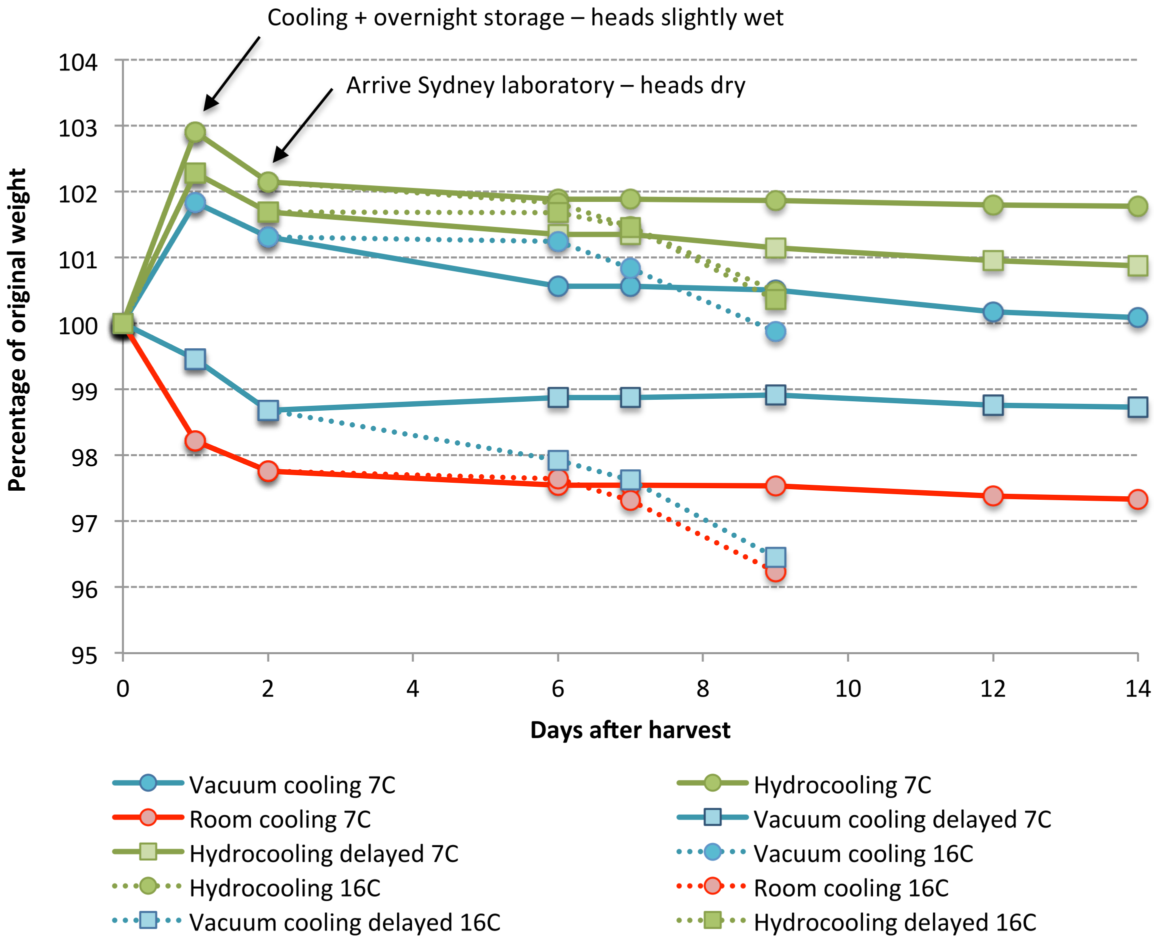


Figure 13. Weight gain / loss of broccoli cooled immediately or after 24 hours delay using a hydro-vacuum cooler, hydrocooler or room cooling. Broccoli was then transported to Sydney and stored at 7C or 16C.

4.3.2. Manjimup trial results

Data from Hobo loggers in the hydro-vacuum cooler was lost due to damage to these loggers when under vacuum. Therefore only data from the i-buttons inserted into the broccoli stems is presented.

Hydro-vacuum cooling was clearly faster than room cooling, with a cooling rate approximately 10 times faster than that of room cooling (Figure 14). It is likely that if the room-cooled broccoli was in a large commercial bin instead of a small crate, that the cooling rate would have been even slower.

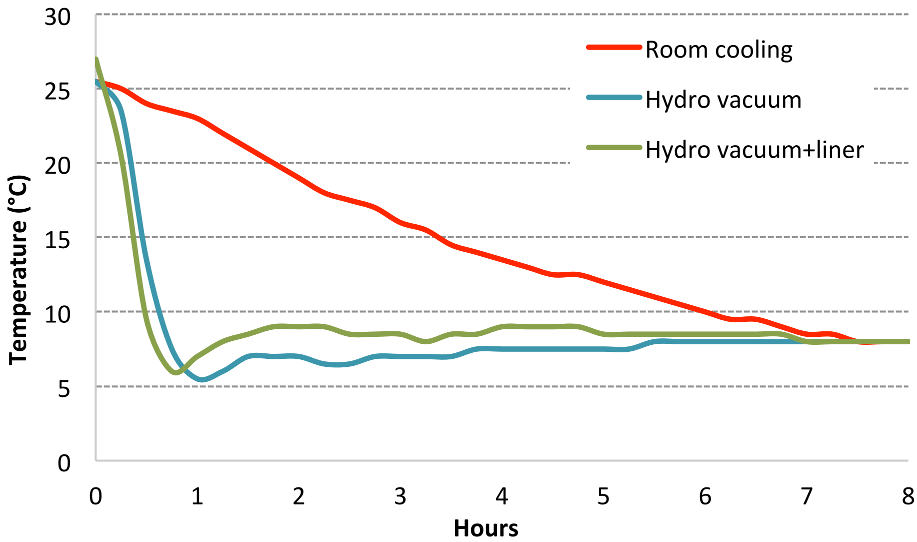


Figure 14. Temperatures inside broccoli stems room-cooled, or cooled using a hydro-vacuum cooler with the broccoli inside a crate only, or inside a crate with an LDPE liner.

Hydro-vacuum cooling broccoli inside an LDPE liner did not affect the cooling rate compared to broccoli packed into a crate only. However, the liner partly filled up with water during cooling, resulting in saturated broccoli heads. If broccoli is packed into liners then holes need to be included to allow the water to drain. While there was no significant difference between these treatments in terms of weight gain during hydro-vacuum cooling, both were different to broccoli that was room cooled (**Error! Reference source not found.**).

Table 3. Weight change of broccoli between harvest and arrival in Sydney from three different cooling methods. Different letters indicate means that are significantly different (p<0.05).

Cooling method	Weight change (%)
Room cooling	-1.11 b
Hydro-vacuum	+6.62 a
Hydro-vacuum in LDPE liner	+5.19 a

The three different cooling methods tested resulted in similar quality at both of the storage temperatures used in this trial. While there was a trend to improved quality in the broccoli that was hydro-cooled with a liner relative to that which was room cooled, this was not significant (p>0.05) (**Error! Reference source not found.**).

Table 4. Quality assessment of broccoli cooled by different methods using a scale of 1–5, where 1=excellent and 5=very poor. Assessments made following 7 days transport from Manjimup to Sydney then either 3 days at 16°C or 8 days at 7°C.

Treatment	Stored at 16°C for 3 days*			Stored at 7°C for 8 days*		
	Colour	Quality	Rots	Colour	Quality	Rots
Room cooling	3.3	3.6	1.8	3.1	3.4	1.3
Hydro-vacuum	3.5	3.8	2.0	3.5	3.4	1.8
Hydro-vacuum + LDPE	3.2	3.5	1.5	3.0	3.0	1.3

* No significant differences were found between any of these mean values (p>0.05)

4.4. Conclusions

In these trials, few quality differences were observed between the treatments. Even broccoli that was stored overnight at approximately 16°C before cooling retained good quality during subsequent storage and shelf life. The slight improvements observed in broccoli hydro-vacuum cooled immediately after harvest or hydro-vacuum cooled with a liner were not statistically significant in this trial, although a larger trial may have found greater differences.

It was somewhat surprising that so few differences were found between vacuum cooling and room cooling despite distinct differences in cooling rates. However, in these trials only small quantities of broccoli were room cooled in well ventilated plastic crates. In the previous project (VG13086) some of the broccoli in bins took between 14 hours and 2 days to 7/8 cool. As this broccoli had been harvested at nearly 40°C, this meant that nearly all of the samples monitored were above 5°C for 2 days. Under such extreme conditions, it would be expected to observe much greater differences due to cooling method.

The primary difference between the treatments was in terms of weight gain/loss. There is a clear advantage of hydrocooling over other methods, although immediate vacuum cooling also ensured that head weight was more than retained. As weight determines head firmness and turgidity, this gain in moisture could also subtly improve overall quality.

Hydrocooling and hydro-vacuum cooling increased the weight of broccoli by 5% compared to room cooling. This represents a significant increase in profits for the grower, with no additional inputs required.

The internalisation of water that occurs during both hydrocooling and hydro-vacuum cooling may offer other opportunities as well.

A wide range of different techniques have been explored in seeking to extend broccoli storage life. Many of these appear to rely in part on the relationship between yellowing of broccoli and its respiration rate. That is, as respiration rate is decreased − by cold storage or modified atmospheres − yellowing is also decreased. This suggests that declines in carbohydrate reserves, particularly in the delicate florets, may be a key trigger for senescence[21].

[21] Irving DE, Joyce DC. 1995. Sucrose supply can increase longevity of broccoli (*Brassica oleracea*)

Recent research has shown that providing an exogenous supply of 12% sucrose (+0.05% bleach) can significantly increase broccoli storage life at 20°C. The treatment retained chlorophyll, and therefore colour, as well as delaying the decline in some of the key phytonutrients that broccoli contains[22]. While this research was conducted at 20°C, with stems kept continuously in the solution, this suggests that sugar levels may be critical to broccoli storage life.

It is unknown whether cooling broccoli in a solution containing sugars (and a biocide) would provide any benefit in terms of storage life. It is possible that uptake of the solution would not be as great as uptake of water, due to its osmotic potential, but that would also need to be determined.

Further trials could test this theory, examining whether an exogenous supply of carbohydrates during cooling can delay yellowing of broccoli florets.

branchlets kept at 22°C. Plant Growth Reg. 17:251-256.

[22] Feng X et al. 2016. Reducing yellowing and enhancing antioxidant capacity of broccoli in storage by sucrose treatment. Postharvest Biol. And Technol. 112: 39-45.

5. Testing the SmartFresh® In-Box system

5.1. Introduction

Traditionally, Australian broccoli has been packed into 8kg polystyrene cartons topped with 2.5–4kg of flaked ice. This system can buffer broccoli from temperature fluctuations during transport and storage, ensures that heads stay fully hydrated, and looks good when buyers open the box.

However, ice also has many disadvantages. Creating ice requires potable water and large amounts of energy, so adds significant cost to the packing process. Ice that is supercooled (it can be as low as -20°C) has the potential to cause freezing damage to the delicate florets. If the ice melts then broccoli ends up sitting in melt-water, causing stem splits and disease. Ice adds weight to the load so can increase transport costs, especially if broccoli is air-freighted to export markets. Even if transport is based on volume rather than weight, styrofoam boxes take up more space on a pallet than a similar cardboard box and hold 8kg of broccoli instead of 10kg, so transport costs are still increased. Finally, styrofoam cartons are difficult to recycle and non-biodegradable, so are not an environmentally sustainable packaging option.

Although many customers expect to see ice in broccoli boxes, there is considerable evidence that it does not improve quality. Broccoli stored at 1°C with ice, an ice replacement or plastic lined fibreboard boxes was all of similar quality on removal and after two days at 20°C[23]. This result is similar to a trial which compared thoroughly pre-cooled broccoli packed in waxed cartons with liners to broccoli packed in styrofoam containers, with both packaging types with and without ice. After 6 weeks storage at 1°C , broccoli packed without ice were rated as better market quality than broccoli packed with ice, regardless of the packaging type used[24].

There is an increasing move away from ice-based systems to ones based on packaging (liners or wraps) and accurate control of the cold chain. However, many suppliers and wholesalers remain unconvinced that broccoli packed this way can retain freshness to retail.

The major cause of quality loss of broccoli is yellowing of the florets due to chlorophyll breakdown. This reaction is mediated in part by ethylene, which may be present in the environment but is also produced by the broccoli head itself[25]. Wills *et al*[26] reported that

---

[23] Kleiber A, Jewell L, Simbeya N. 1993. Ice or an ice-replacement agent does not improve refrigerated broccoli storage at 1°C. HortTech. 3:317-318.

[24] Tan SC, Berston J, Haynes Y. 1992. Packaging systems for sea freight of broccoli. NZ J. Crop Hort. Sci. 20:167-172.

[25] Tian MS et al. 1994. A role for ethylene in the yellowing of broccoli after harvest. J. Amer. Soc. Hort. Sci. 119:276-281.

[26] Wills RBH et al. 1999. Importance of low ethylene levels to delay senescence of non-climacteric fruit and vegetables. Aust. J. Exp. Agric. 39:221-224.

reducing the ethylene concentration from 0.1ppm to <0.005ppm doubled the storage life of broccoli held at 20°C or 5°C.

The compound 1-methylcyclopropene (1-MCP) has been demonstrated to be extremely effective in both reducing ethylene sensitivity and inhibiting ethylene production in a range of fruit, vegetables and flowers. Marketed as 'SmartFresh', 1-MCP is used extensively for storage of apples, as well as for pears, persimmons, and a range of other fruit crops.

SmartFresh® is also registered for use on broccoli, having been demonstrated to be effective at reducing floret yellowing. For example, treatment with 1ppm 1-MCP almost completely inhibited yellowing for 9−18 days during storage at 10°C[27]. Extensions in storage life of over 200% have been reported at 5°C and 20°C[28]. Moreover, the effects of 1-MCP may be retained during longer periods of cold storage, with the result that broccoli yellows more slowly when placed on retail display[29].

Although SmartFresh® appears to offer an alternative to ice in terms of maintaining freshness of broccoli, and is registered for that purpose, it has not found commercial application. This is in part due to the logistical difficulties of treatment. As 1-MCP is applied as a gas, broccoli must be placed in a sealed chamber for treatment. Treatment at >10°C is recommended, as it is fast and effective, although products can be treated as low as 1°C if exposure times are increased[30].

This is not consistent with the usual handling methods for broccoli, which is harvested into bins, precooled, then packed into either lined cartons or styrofoam with ice. It may then be returned to the same cold room for storage until dispatch. This is very different, for example, to apples, which may be stored for months. Cool rooms are rarely shut for long, temperatures are low, and if broccoli is field packed then exposure within a cool room may be ineffective.

The new SmartFresh® In-Box system could make this technology easier to use and therefore more attractive. The In-Box sachets are simply added to the product, which is packed inside a liner. AgroFresh (the Company that markets In-Box) has developed a special 'RipeLock' liner for use with In-Box. The liner is designed to be less permeable to 1-MCP than a standard LDPE liner, although it superficially appears similar. Testing of In-Box sachets in South Africa found positive effects for the system when used with broccoli, with the reduced rates of yellowing most significant when broccoli was stored at 7.5°C or 12°C[31]. Although

[27] Fan X, Mattheis JP. 2000. Yellowing of broccoli in storage is reduced by 1-methylcyclopropene. HortSci. 35:885-887.

[28] Ku VVV, Wills RBH. 1999. Effect of 1-methylcyclopropene on the storage life of broccoli. Postharvest Biol. Technol. 17:127-132.

[29] Ekman JH, Pristijono P. 2010. Evaluation of new shipping technologies for Australian vegetables. HAL project VG06045, Final Report.

[30] Fernandez-Leon MF et al. 2013. Different postharvest strategies to preserve broccoli quality during storage and shelf life: controlled atmosphere and 1-MCP. Food Chem. 138:564-573.

[31] deBeer T, Crouch EM. 2014. Maintaining broccoli shelf-life during mixed load marketing with a novel in-box 1-methylcyclopropene and modified atmosphere packaging system. ActaHort 1079:179-

shelf life was increased, it appeared that the increase was not as great as reported previously for broccoli fumigated with 1-MCP. However, in this case only a single In-Box sachet was added to each carton (volume not stated). It is possible that adding more than one sachet may further enhance the results.

Two trials were therefore conducted testing the SmartFresh® In-Box system with broccoli. The trials took place at commercial facilities in Werribee, Victoria and Manjimup, WA with the assistance of representatives from AgroFresh Pty Ltd, who supplied expertise, labour and materials for these trials.

5.2. Method

5.2.1. Werribee trial

This trial was designed so as to test how the SmartFresh® In-Box system could be applied commercially. Broccoli was hand-harvested at the farm in Werribee on 14 December, 2015. The heads were immediately returned to the packing shed and divided into 21 approximately equal units. Within each unit six heads were randomly selected, tagged and weighed with weight recorded. Data-loggers (i-button temperature) were inserted into the stems of seven heads of broccoli, taped up and marked with flagging tape.

All of the broccoli samples were loaded into plastic crates and hydro-vacuum cooled. On removal from the hydro-vacuum nine units (three treatments x three replicate units) were set up immediately. The remaining 12 units (four treatments x three replicate units) were stored overnight, as would be normal commercial practice, and set up the following morning.

Figure 15 - Tagged broccoli in crates (left) and the hydro-vacuum cooler loaded with lettuce

Treatments were:

1. Packed 14 December
    a. Carton with standard LDPE liner

186.

b. Carton with standard LDPE liner + 4 x In-Box sachets
c. Carton with RipeLock liner + 4 x In-Box sachets

2. Packed 15 December
    a. RipeLock liner
    b. LDPE liner + 4 x In-Box sachets
    c. RipeLock liner + 4 x In-Box sachets
    d. Styrofoam box with top icing

The LDPE and RipeLock liners with In-Box were closed by pushing as much air as possible out of the bag, twisting the top and knotting to form an airtight seal.

Figure 16. SmartFresh® In-Box sachets with broccoli, and packed inside the sealed RipeLock liner.

When all treatments were complete, the cartons were palletised and stored before overnight refrigerated transport to Sydney Markets. The samples were then collected and transferred to the laboratory at Sydney University for storage life assessment.

On arrival all heads were weighed and assessed for quality attributes including:
- Colour (by comparison with photographic scale)
- Overall marketability / acceptability
- Presence of rots in florets or stem

Quality attributes and weight of broccoli heads at 16°C were evaluated daily, while heads at 7°C were evaluated twice weekly. Assessments continued until the broccoli was no longer considered marketable.

5.2.2. Manjimup trial setup

Broccoli (variety Aurora) was harvested between 7am and 8am on 7 March, 2016 from a commercial broccoli farm near Manjimup, WA. Broccoli was returned to the pack house and cooled thoroughly within three hours of harvest using a hydro-vacuum cooler.

Broccoli was then divided into 18 equal units. One treatment x three replicate units was set up immediately, the remainder were stored overnight and set up the following morning.

Treatments were:

1. Packed 7 March
    a. RipeLock liner + 4 x In-Box sachets
2. Packed 8 March
    a. LDPE liner
    b. RipeLock liner
    c. LDPE liner + 4 x In-Box sachets
    d. RipeLock liner + 4 x In-Box sachets
    e. Styrofoam box with top icing

When all treatments were complete, the cartons were palletised and stored before refrigerated transport to Sydney, with transfers in Perth and Adelaide. The samples were collected six days later on 14 March and transferred to the postharvest laboratory at University of Western Sydney, Hawkesbury for shelf-life assessment.

On arrival at the postharvest laboratory all heads were weighed and assessed for quality attributes including:

- Colour (by comparison with photographic scale)
- Overall marketability / acceptability
- Presence of rots in florets or stem

The units were then divided into two – half of the heads were stored at 7°C and the remainder at 16°C. These temperatures were used as they correspond to average retail temperatures in refrigerated and non-refrigerated display units. Storage conditions were monitored with temperature and relative humidity data-loggers.

Quality attributes and weight of broccoli heads at 16°C were evaluated daily, while heads at 7°C were evaluated twice weekly. Assessments continued until the broccoli was no longer considered marketable.

5.3. Results

5.3.1. Werribee trial results

Broccoli that was inside a sealed RipeLock bag + In-Box yellowed more slowly and retained quality at 5°C better than broccoli that was inside an LDPE bag. Delaying treatment for 24 hours did not reduce the effectiveness of the In-Box treatment.

When In-Box sachets were placed inside an LDPE bag they were less effective at retarding yellowing than when the RipeLock bag was used – consistent with a higher rate of permeation of 1-MCP through LDPE film.

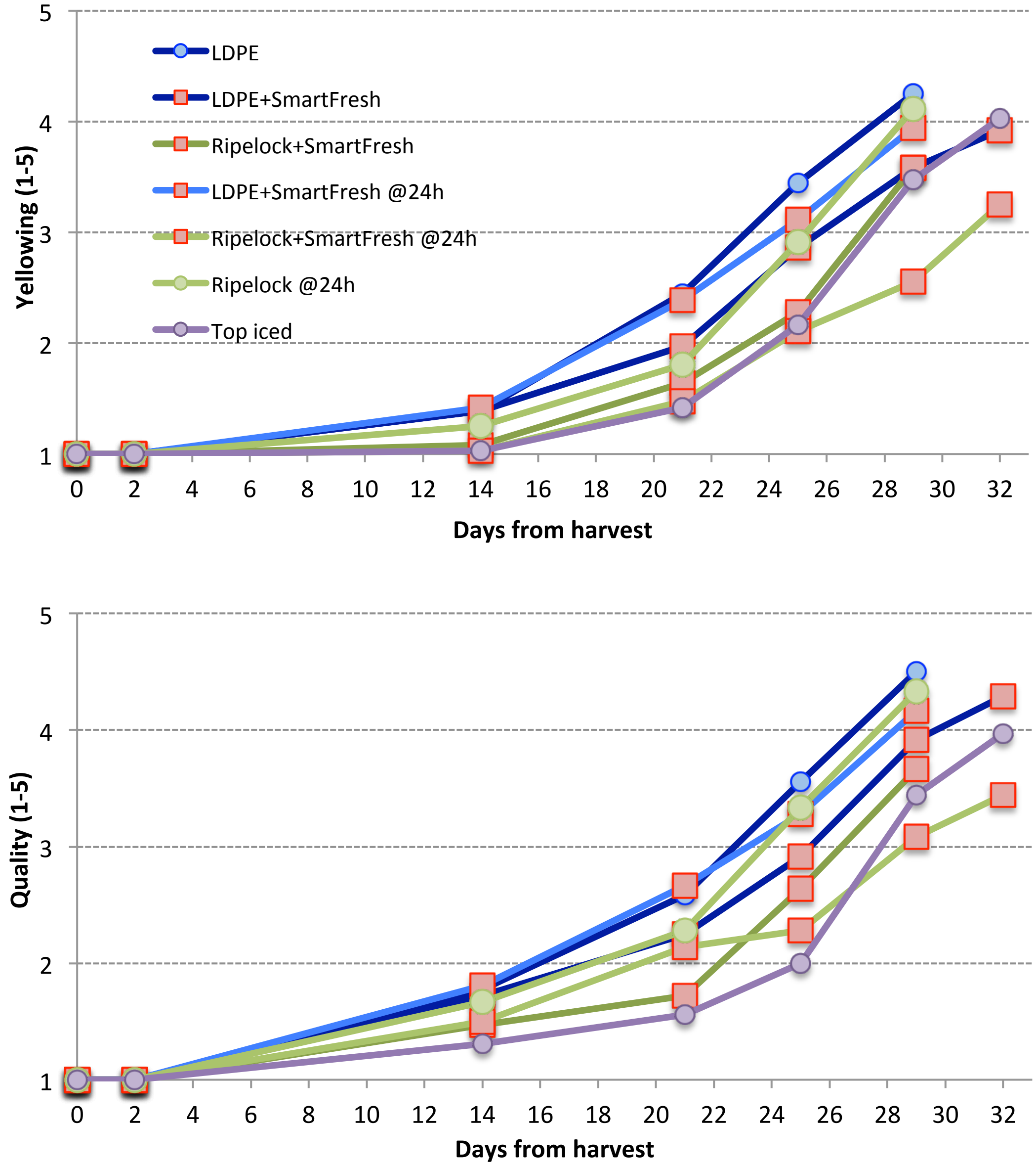


Figure 17. Changes in colour (top) and quality (below) of broccoli stored at 5°C following packaging in LDPE film or RipeLock film with / without 4 x SmartFresh In-Box sachets, applied immediately after cooling or with a 24 hour delay, or packed in a styrofoam carton with top icing.

As a result of delayed yellowing, broccoli treated with SmartFresh® and packed in a RipeLock bag remained marketable for approximately 23 days following harvest and storage at 5°C. This was similar to broccoli that was top-iced and packed in styrofoam. In contrast, broccoli packed in a cardboard carton with LDPE liner remained marketable for around 18 days, regardless of whether In-Box sachets were added.

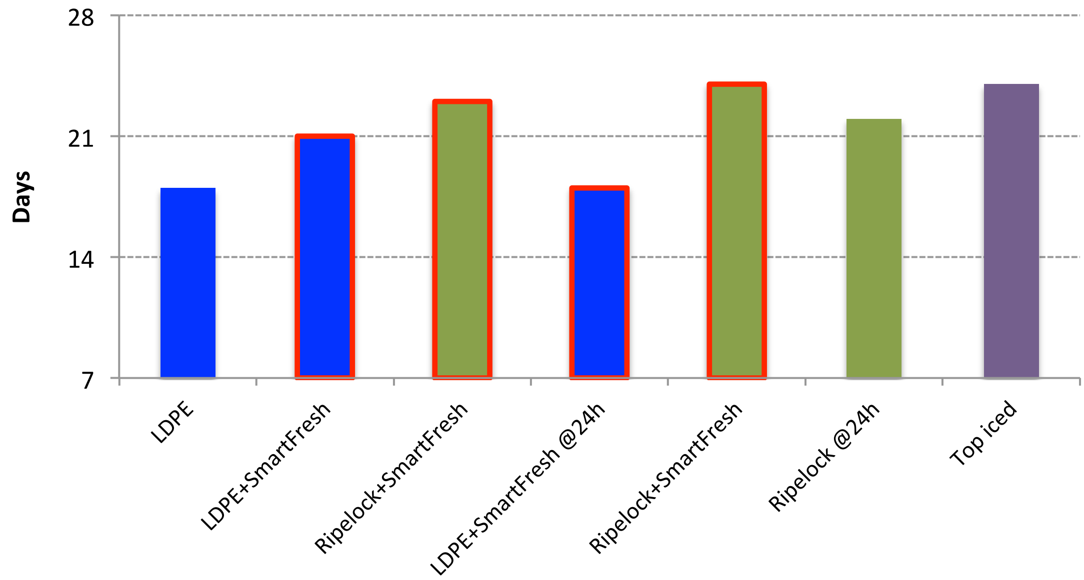


Figure 18. Days broccoli was still marketable following packaging in LDPE film or RipeLock film with / without 4 x SmartFresh In-Box sachets applied immediately after cooling or with a 24-hour delay, or packed in a styrofoam carton with top icing. Broccoli stored at 5°C.

The results were analysed by factor to separate differences due to packaging type and In-Box treatment. Yellowing was significantly faster in the LDPE liner compared to the RipeLock liner and top icing, and significantly slower when In-Box was added to the package (**Error! Reference source not found.**).

Table 5. Differences in yellowing due to packaging type and treatment with SmartFresh In-Box. Letters indicate means which are significantly different.

	Colour grade					
	21 days		**25 days**		**29 days**	
LDPE liner	2.27	b	3.14	b	3.93	b
RipeLock liner	1.64	a	2.44	a	3.42	a
Top iced	1.42	a	2.17	a	3.47	a
No SmartFresh	1.89	a	2.84	b	3.94	b
SmartFresh	1.87	a	2.59	a	3.42	a

5.3.2. Manjimup trial results

The supply chain between Manjimup and Sydney was not well managed, with temperatures of broccoli inside the cartons being between 5°C and 10°C for several days, and rising to around 13°C during trans-shipment in Perth.

The broccoli packed in styrofoam cartons with top icing was protected from these fluctuations and remained below 5°C until it reached Sydney. In this case, the top icing did what it was originally designed to do, keeping the broccoli cool despite breaks in the cold chain.

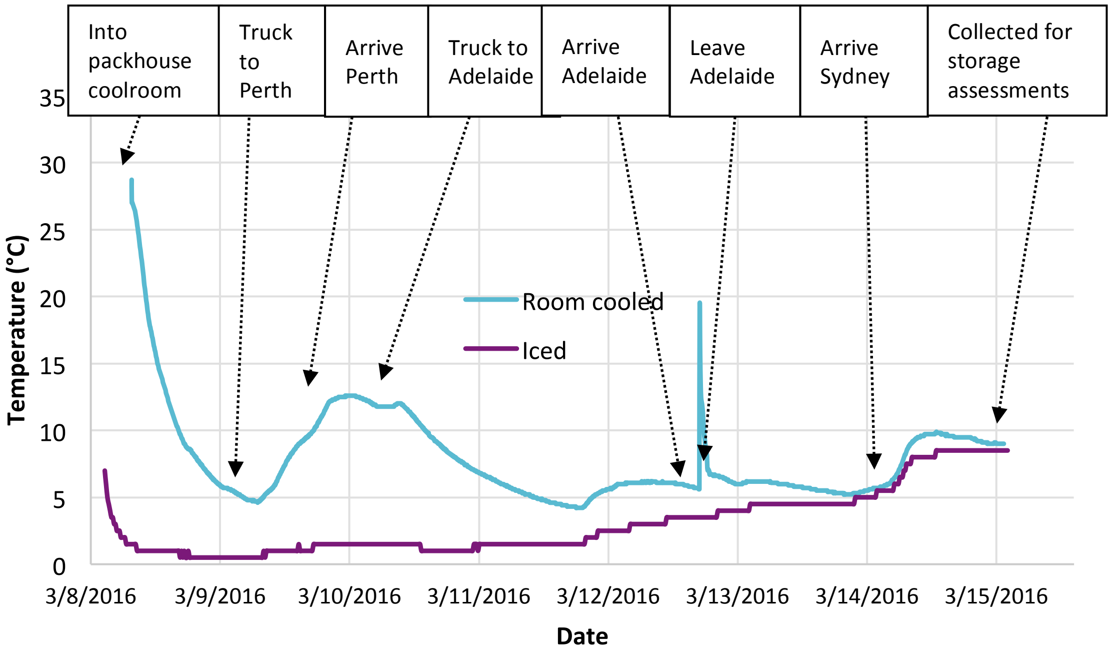


Figure 19. Temperature log inside an iced styrofoam box and a room-cooled carton of broccoli during transport from Manjimup to Sydney.

It is likely that this temperature abuse during transport contributed to the relatively poor results for broccoli packed in LDPE or RipeLock films, when compared with the broccoli packed in styrofoam and ice. However, despite a reasonably severe temperature challenge, broccoli treated with SmartFresh In-Box performed as well, or almost as well as broccoli packed in ice. The best results were achieved when the broccoli was treated as soon as possible after harvest and packed in RipeLock film.

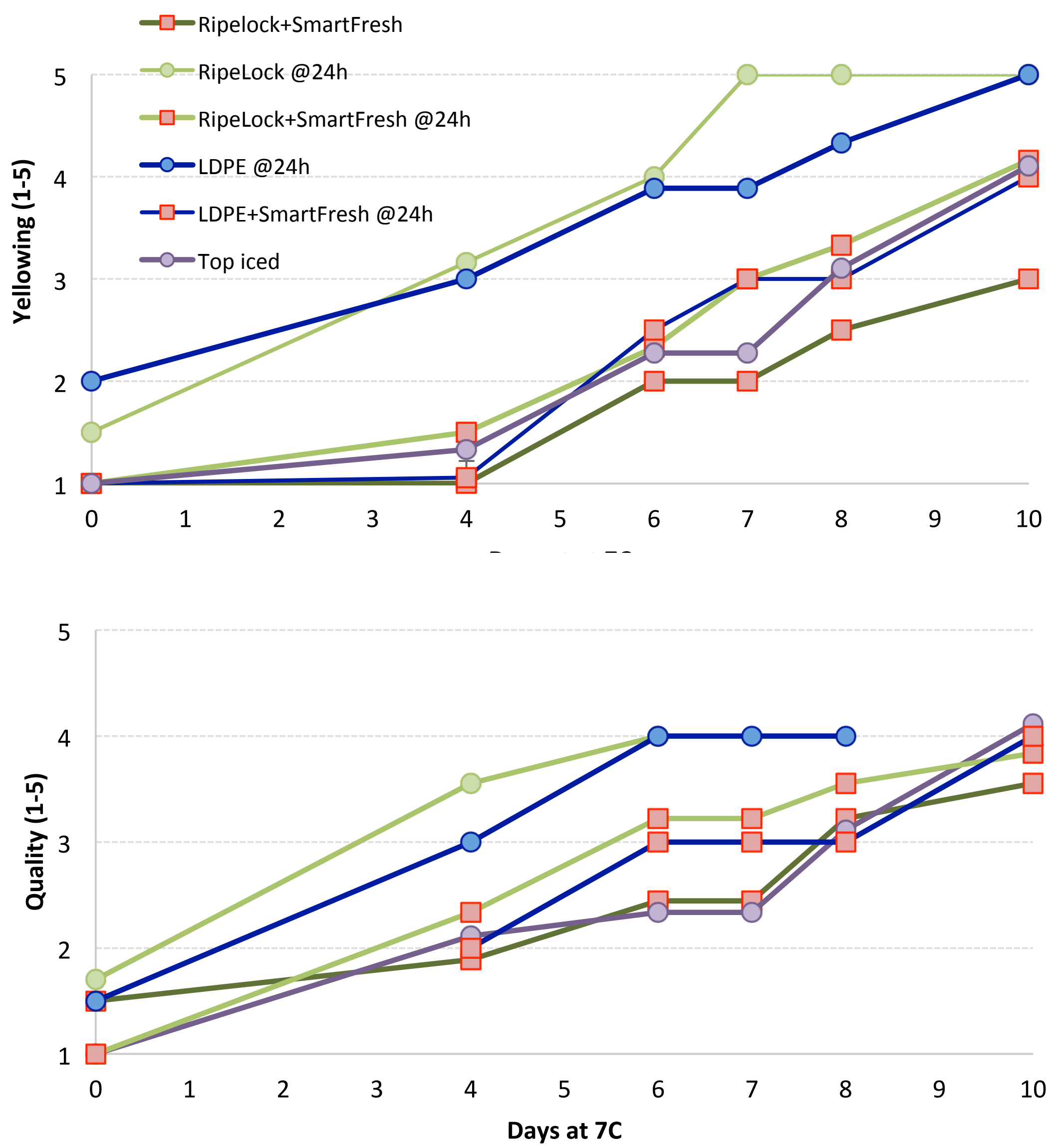


Figure 20. Changes in colour (top) and quality (below) of broccoli transported from Manjimup to Sydney then stored at 7°C. Broccoli was packaged in LDPE film or RipeLock film with / without SmartFresh In-Box sachets applied immediately after cooling or with a 24-hour delay, or packed in a styrofoam carton with top icing.

As a result of delayed yellowing, broccoli treated with SmartFresh® remained marketable for approximately 1 week after arrival in Sydney when placed under simulated retail display at 7°C. This gave it a similar retail storage life to broccoli packed in ice, even though it had been subjected to much higher temperatures during transport (Figure 21). Differences between the treatments were smaller when broccoli was placed at 16°C due to the fast rate of deterioration. However, there were significant differences between SmartFresh® treated and non-SmartFresh treated broccoli at both temperatures (Table 6).

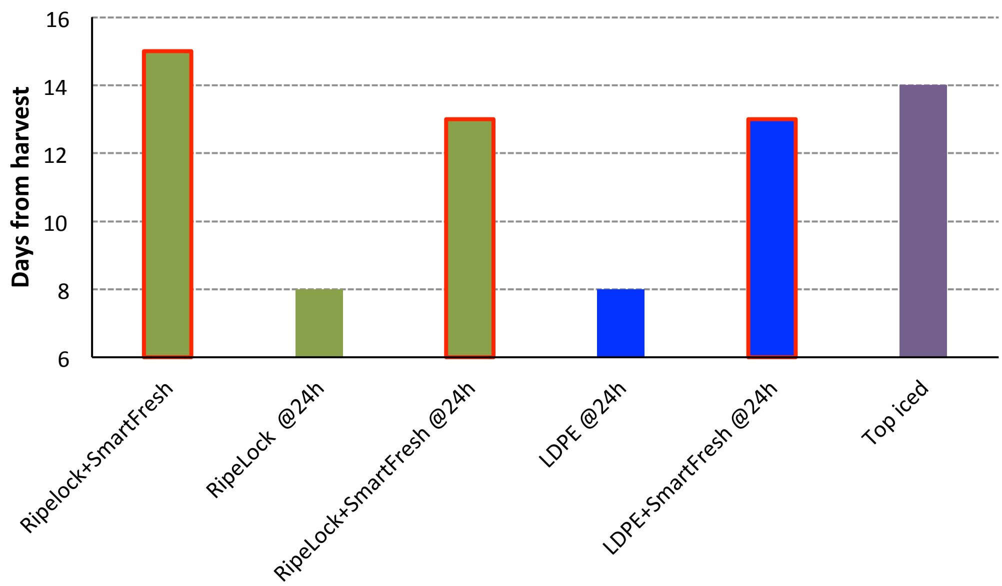


Figure 21. Days that broccoli remained marketable after transport from Manjimup to Sydney then storage at 7°C. Broccoli was packaged in LDPE film or RipeLock film with / without SmartFresh In-Box sachets applied immediately after cooling or with a 24-hour delay, or packed in a styrofoam carton with top icing.

Table 6. Effect of different packing treatments on colour, appearance and rot development during simulated retail display at 16 or 7°C following transport from Manjimup to Sydney. Subjective assessment made using a scale of 1-5, where 1=excellent and 5=very poor Letters indicate means that are significantly different (p<0.05).

Packaging treatment	Stored at 16°C for 2 days			Stored at 7°C for 4 days		
	Colour	Quality	Rots	Colour	Quality	Rots
RipeLock + SmartFresh	2.0 a	2.0 a	2.0 bc	1.0 a	1.9 a	1.4 a
RipeLock @24h	3.0 b	3.2 b	2.3 bc	3.2 b	3.6 c	1.4 a
RipeLock + SmartFresh @24h	2.0 a	2.1 a	1.2 a	1.5 a	2.3 ab	1.3 a
LDPE @24h	3.1 b	3.4 b	2.4 c	3.0 b	3.0 bc	1.9 a
LDPE + SmartFresh @24h	2.1 a	2.4 a	2.4 c	1.1 a	2.0 a	1.9 a
Top iced	2.0 a	2.2 a	1.9 a	1.3 a	2.1 a	1.1 a

5.4. Conclusions

The results from these two trials suggest that treatment with the SmartFresh® In-Box system can provide broccoli with similar protection from fluctuating cold chain temperatures to top icing. Results were best when the In-Box sachets were combined with the RipeLock liner. This supports the claim that this material is more resistant to diffusion of 1-MCP than standard LDPE film.

While the best results may be gained by treating broccoli immediately after harvest rather than after a 24-hour delay, the data is not conclusive on this point. In the first trial there was no penalty for delaying treatment, while in the second there were only minor significant differences. It seems possible that adding the In-Box sachets the day after packing, which would be the easiest procedure to fit into existing practices, may still provide useful efficacy.

Under effective cold chain conditions, where broccoli is kept below 5°C throughout transport and marketing, SmartFresh® is likely to provide little benefit in terms of improved quality. However, the results suggest that the SmartFresh® In-Box system as the potential to replace top-icing in situations where broccoli may be transported long distances, stored for extended periods, or is likely to be subjected to temperatures higher than optimal. While the cost of the In-Box treatment is likely to be significant, this would be offset by reductions in packaging, power and transport costs, as well as providing a more sustainable method of packing broccoli.

6. Energy costs of cooling broccoli

6.1. Introduction

Cooling broccoli is, in some ways, adding value with electricity. While producers know that broccoli quality is maximised at close to 0°C, reducing the temperature of large volumes of product, especially if harvested while warm, is a major expense. Some packers may feel this expense is poorly justified, especially if supply chains are short and prices are low. However, failing to pre-cool broccoli properly when it first arrives from the field may not only negatively affect quality, but actually increase cost during subsequent storage.

Energy is therefore a significant cost for broccoli growers and packers. The common methods of vegetable cooling have been applied to broccoli to estimate the energy required for each process. This has been achieved by using the theoretical energy in 1 tonne of broccoli, to determine an energy efficiency factor for each method (= theoretical/practical x100%). These calculations have been compared to field energy consumption data where available. A significant variation in field performance has been observed due to individual circumstances, throughputs and refrigeration system efficiencies.

6.2. Theoretical energy and cooling rates for broccoli

The amount of energy used to cool broccoli from the field is dependent on the difference between the temperature of the field broccoli and the target temperature (ΔT). For our calculations, we have assumed a field temperature of 20°C and a target temperature of 4°C (ΔT=16). These estimates can be considered approximately proportional to the temperature difference if these are varied.

Cooling broccoli requires the removal of ***sensible heat***[32] from the plant.

Energy used in cooling broccoli	**Cooling from 20°C to 4°C**	
	Broccoli Heat Capacity Cp 4.0 (kJ/°K-kg)	
	Theoretical 'sensible' heat extracted = 4.0 x 16 kJ/kg	
	64	kJ/kg
	64	MJ/T

Various cooling systems are employed for this purpose. These include forced air systems in a cool store, hydrocooling with cold water or vacuum cooling. Unlike in the USA, ice is not usually used alone to cool broccoli. However, top icing may be used in conjunction with

[32] ***Sensible heat*** is the energy removal required to reduce the temperature in the broccoli to the target. It is calculated as the mass x change in temperature x heat capacity.

other pre-cooling measures. All of these methods have individual advantages and drawbacks. A key factor in energy use by these methods of cooling is the time it takes to get the broccoli to the target temperature, as other energy losses can occur during this cooling period.

The broccoli itself has an inertia to cooling as the stalks require cooling through to their core. The following calculation provides an estimate of the cooling rate inherent in the broccoli.

Heat transfer in broccoli	**Thermal conductivity of broccoli 0.381 W/m°K**
	Surface area of broccoli 1.515 m^2/g
	Density of broccoli 0.385 g/cm3
	Average thickness = 1/(1.5*.385) cm =1.73 cm
	Thermal conductance at 0.86 cm thickness = 44 W/m2°K
	Heat transfer Q/T = ΔT x k x Area/T = 106 kW/T
	= 381 MJ/sec.tonne
	Rate of cooling possible = 120 °K/sec at ΔT=16
	Half-life for cooling from 20 C ~ 6 msec.

The thickness of the broccoli varies from the leaves, florets and stalks and the loss of heat from the centre of the stalks is the slowest process. For our purposes, we have assumed an average stalk thickness (1.73 cm) calculated from a basic surface area of plant, as determined by Applied Horticultural Research. Heat transfer was calculated at a maximum of 106 kW per tonne, making a cooling rate of 120°C per second theoretically possible if this heat is instantaneously removed from the plant surface.

The methods employed have a cooling period that is potentially much greater and so they have factors that determine the rate of cooling rather than the broccoli itself.

6.3. Hydrocooling broccoli

Hydrocooling employs chilled water sprayed over the bins of broccoli, or chilled water in which the broccoli may be immersed. The most common method of hydrocooling is when water is sprayed over bins that are moving through a tunnel or are stationery.

Chilled water is generated through a water chiller system and is stored in a chilled water tank. The water extracts the heat from the broccoli. Generally, the time taken to hydro-cool broccoli is about 30 minutes. This is due to the transfer of heat between the broccoli and the water, and water temperature increasing through the storage and piping systems. Water movement across the surface of the broccoli is considered to be a determining factor of the cooling rate. Water at the surface will warm up and its movement from the surface is dependent on turbulence and water-flow rates.

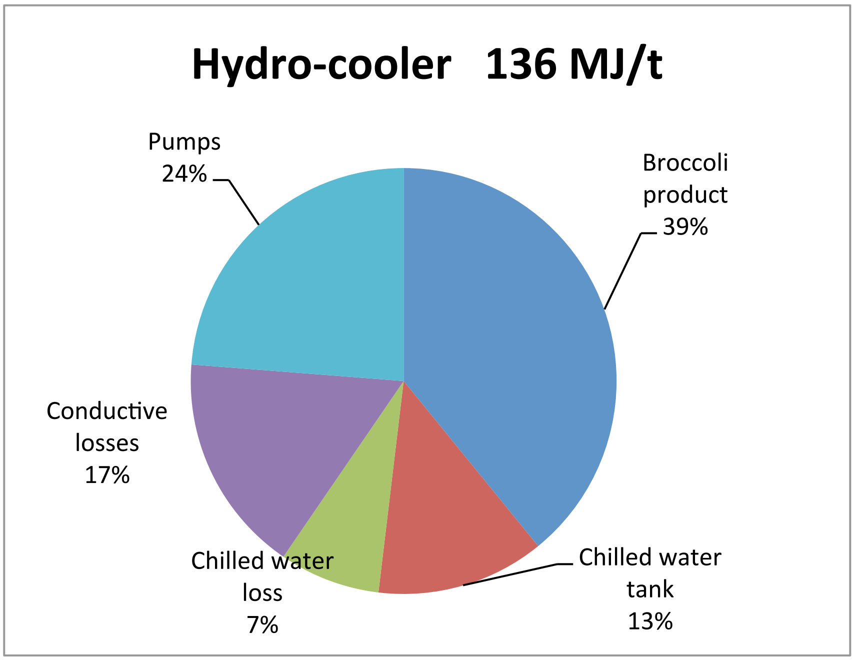
Losses will also occur during this process. Chilled water is lost on the broccoli as it passes through the hydro-cooler, and if recycled, the water has to be replenished regularly.

Indicative Hydro-cooler energy consumption

Hydro cooler						
Capacity		6	Tonne/hour	Water Cp	4.18	kJ/kg°C
Chilled water storage		15	m^3	Ambient	20	°C
				Heat	1,254	MJ/tank
Flow rate		5.2	L/sec			
ΔT (°C)		7	°K	Q	548	MJ/h
					91	MJ/Tonne
Chilled water losses		900	L/h	Q	752	MJ/day
Pump losses	Run time	10 h	30 kW	E	180	kWh/day
					11	MJ/t
Daily energy		10	hours	60	T/day 6,731	MJ/day
				TOTAL	**136**	**MJ/tonne**

Water is an effective heat transfer medium, but it has to itself be cooled. As such, chilled water losses represent the greatest problem for energy efficiency. The energy efficiency in this case is 47%, which may be considerably improved through higher throughput.

This situation is fairly typical for the hydro-coolers investigated in 2014 for medium to larger processors. Chilled water was disinfected and recycled through the day, but discharged overnight and replaced with fresh water each morning. Hydro-cooler water losses and conductive losses through the tanks and piping also contribute to cooling energy consumption.



Graham Thorpe[33] of Victoria University conducted a study on hydrocooling broccoli published in 2008. His data and that of Harrup and Holmes[34] showed that 80% of the cooling was achieved in 35 minutes from a field temperature of 30°C using water at 0°C.

6.4. Air-cooled broccoli

Cool stores work by passing air over cold evaporator coils and thus cooling the air to a set temperature. They frequently utilise forced air cooling for vegetables, such as broccoli, after packaging. Chilled air is directed over the packaged broccoli on pallets until it reaches its target temperature. This is a longer process than hydrocooling as air has a lower heat capacity than water and its contact with the product may be compromised by the packaging.

Typically, broccoli may take 6 to 10 hours to cool from 20 to 4°C, with forced air cooling and considerably longer without forced air, in a cool store.

The process of cooling is the same as with water cooling except that the heat capacity (Cp[35]) for air is three orders of magnitude less than that of water per unit volume. So over 1,000 times more air volume is required to contact the broccoli to achieve the same heat removal at the same temperature.

Cool stores also suffer from same sorts of losses in the chilled air through heat conduction with structures and extraneous heat sources, such as fan and forklift motors. These losses depend on construction, throughput and operating temperatures.

A typical cool store operation follows.

[33] Design and Operation of Hydrocoolers - Graham Thorpe - Smart Water Fund report 2008

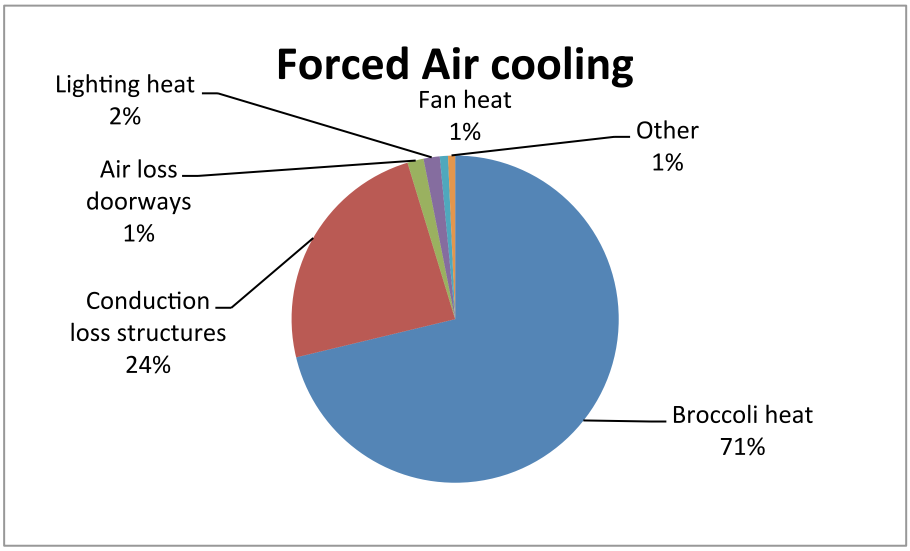
[34] Harrup, P. G. and Holmes, R. J. (2001) An evaluation of a prototype broccoli hydrocooler, A confidential report prepared by the Institute of Horticultural Development

[35] Heat capacity at constant pressure (Cp) in J/°C.g is used in these calculations

Forced air indicative energy consumption

Cool store forced air		**700 m3**	**(75mm Polyurethane insulated panels and a concrete floor)**					
Capacity	30	Tonne	Operation	10	hr	Temperature	2	°C
Structural conductive losses	18	kW		180	kWh			
	64.8	MJ/sec		648	MJ		21.6	MJ/Tonne
Cold air losses	900	m^3/10 h		15	kWh			
	60	kJ/m^3		54	MJ		1.8	MJ/Tonne
Lighting losses	3	400W high bays		12	kWh			
Fan heat	3	2 kW AHUs		6	kWh			
				22	MJ		0.72	MJ/Tonne
Forklifts	5	kW at 10%		5.25	kWh			
/ humans	0.25	kW at 10%		19	MJ		0.63	MJ/Tonne
Broccoli heat	30	Tonne		533	kWh			
	64	MJ/Tonne		1920	MJ		64	MJ/Tonne
						TOTAL	**90**	**MJ/Tonne**
					COP	0.7	35.8	kWh/Tonne

Air cooling is 71% energy-efficient in this case. Efficiency can be improved by further insulation and containment of cold air. Throughput will have a significant effect, as will product storage time.



6.5. Vacuum cooling

Vacuum cooling is a method normally applied to leafy vegetables. However, it has been used to cool cabbage and can be used with broccoli, using water sprayed onto the plant prior to cooling, called ***hydro-vacuum cooling***. The vacuum system works by evaporating the water on the plant's surface, and which has a lower boiling point at the reduced pressure (~ 600 Pa). Cooling occurs due to the take up of latent heat of vaporisation during the phase change from liquid to water vapour.

The latent heat of vaporisation for water is 2,500 MJ/tonne at 0°C, so to cool 1 tonne of broccoli from 20 to 4°C takes the vaporisation of 26kg of water (64 MJ/tonne). This assumes that other systems do not contribute heat to the system.

There is no need to cool ancillary systems, other than packaging. The vacuum formed effectively insulates the product, so heat transfer from containment structures is minimised.

Vacuum cooling is fairly rapid and is controlled by the rate of vaporisation of water at the broccoli surface. This in turn is limited by the movement of water to the surface and the maintenance of the vacuum.

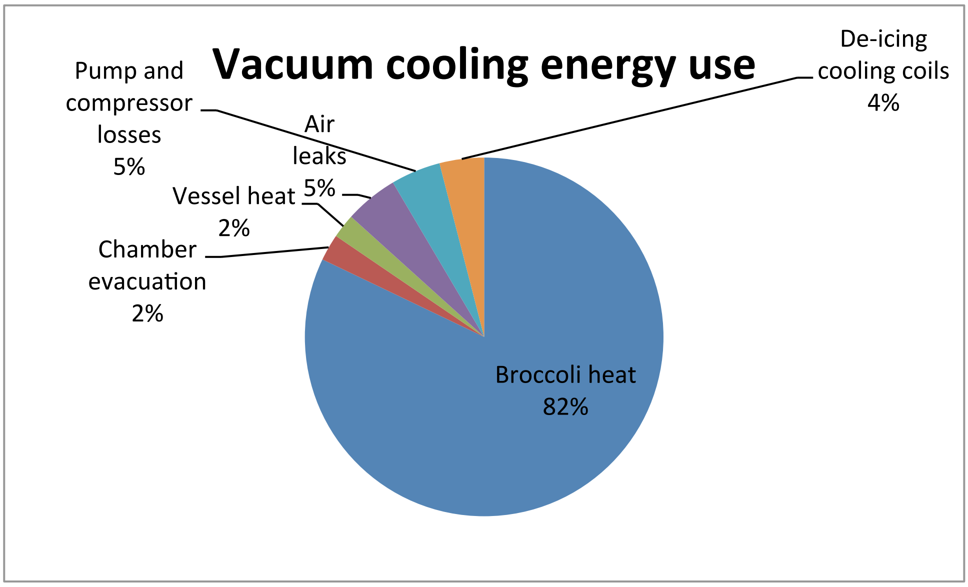
Vacuum cooler indicative energy consumption

Vacuum cooling					**Cycle time**		**Total Energy kWhMJ**		**MJ/Tonne**
Vessel	2.7 x 3.4 x 13.4 m		123	m^3	60	min.			
Vacuum pumps	600	Pa	50	kW	60	min.	50	kWh	
							180	MJ	11
Refrigeration system			250	kW	60	min.	250	kWh	
							900	MJ	56
Evacuation of chamber			50	kW	10	min.	8.3	kWh	
							30	MJ	1.9
Vessel cooling	3	Tonne	452	J/kg.°K			27	MJ	1.7
Air infiltration	123	m^3	50	kW	20	min.	16.7	kWh	
							60	MJ	3.8
De-icing cooling coils	20	kg					50	MJ	3.1
Broccoli	16	Tonne			**Theoretical**		**1024**	**MJ**	**64**
						Totals		MJ	78

The energy-efficiency of vacuum cooling is dependent on maximising the vacuum chamber loads, as the losses are mainly load independent. The chamber air has to be extracted, the vessel is cooled and air leaks occur irrespective of the load.

Vacuum cooling is the most efficient and also fairly quick at cooling broccoli, or other suitable vegetables. The efficiency is 82% with 18% losses from necessary design factors such as vessel evacuation, vessel cooling and losses due to leaks.

Losses are estimated in the following chart.



Thompson, Chen and Rumsey[36] measured the power demand of the vacuum pumps and compressors over the cooling cycle, which showed a consistent vacuum pump demand and a rise and decline of the compressor. Carton cooling accounted for about 10% of the total energy demand in their study.

6.6. Icing broccoli

Icing is commonly used to cool broccoli in the carton. It has the advantage that the presence of ice indicates that cooling is still effective, however, this also indicates that cooling potential is being wasted. When 8kg of ice is applied per 10kg of broccoli for two weeks of storage to maintain the temperature at or near 4°C, large amounts of ice are wasted.

Ice contact with the broccoli surface is poor, leading to uneven cooling and cold water losses from melted ice will also be significant.

Icing	**Function:**	**reduce temperature from 4 to 0°C**
		store broccoli for 2 weeks
Ice used per tonne of broccoli	800	kg/Tonne
Sensible heat removed from broccoli	81.8	MJ/Tonne
Sensible heat removed from water to	2,067	MJ

The energy efficiency of icing to keep broccoli temperature near 0°C for two weeks is about 4%.

[36] Applied Engineering in Agriculture – Thompson, Chen and Rumsey (Vol3. No.2 pp 196-199 1987)

It takes about 1kg of ice to chill 3kg of broccoli from 20°C to 4°C[37]. This is still much less efficient than other available cooling methods.

Icing	**Function:**	**reduce temperature from 20 to 4°C**	
		(no storage allowance)	
Ice used per tonne of broccoli		330	kg/Tonne
Sensible heat removed from broccoli		64	MJ/Tonne
Sensible heat removed from water		853	MJ
Energy used in ice making		1,218	MJ

The energy efficiency of this icing to simply reduce the broccoli temperature from 20°C to 4°C is about 5%.

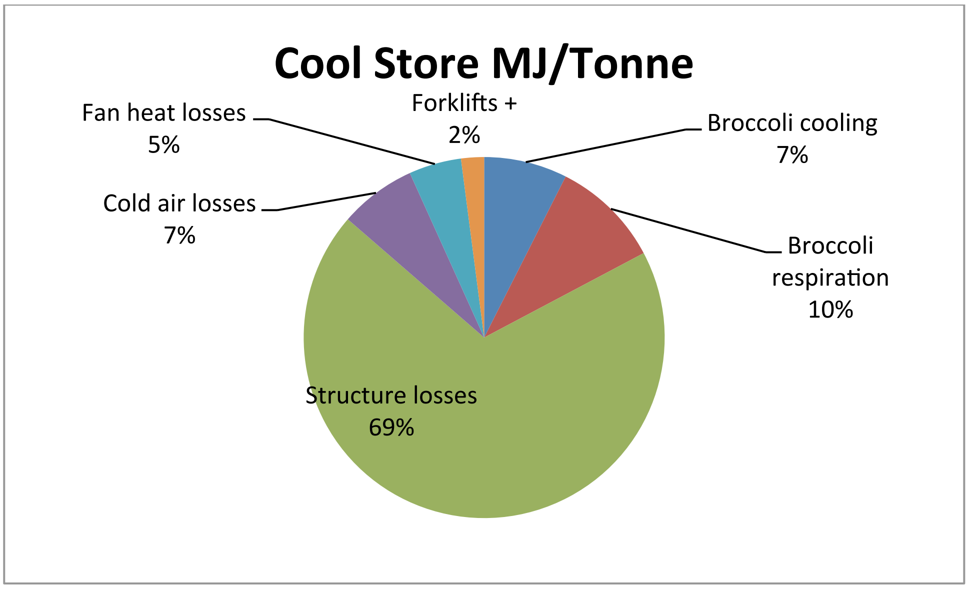
6.7. Cool store cooling of broccoli

Broccoli when packaged may be placed in a cool store, where it will cool gradually. The following estimation of energy is based on two weeks of storage. During this period more energy is consumed in broccoli respiration than cooling from 20 to 4°C.

Broccoli in cool store	**Cooling over two weeks**		**Uninsulated concrete floor**	
30Tonne	Cool store at 4°C			
	30	Tonne	Per Tonne	
Broccoli cooling sensible heat	1,920	MJ/30 Tonne	64	MJ/Tonne
Broccoli respiration over 2 weeks	2,520	MJ/30 Tonne	84	
Conductive heat	17,787	MJ/14d.	593	
Cold air losses	1,769	MJ/14d.	59	
Fan heat losses	1,210	MJ/14d.	40	
Other heat losses	529	MJ/14d.	18	
Total sensible heat to be removed	25,735		858	

Energy efficiency is estimated at 17% mainly due to cool store floor losses.

[37] Horticulture Information Leaflet 801 - NC State University – Wilson, Boyette and Estes 7/99

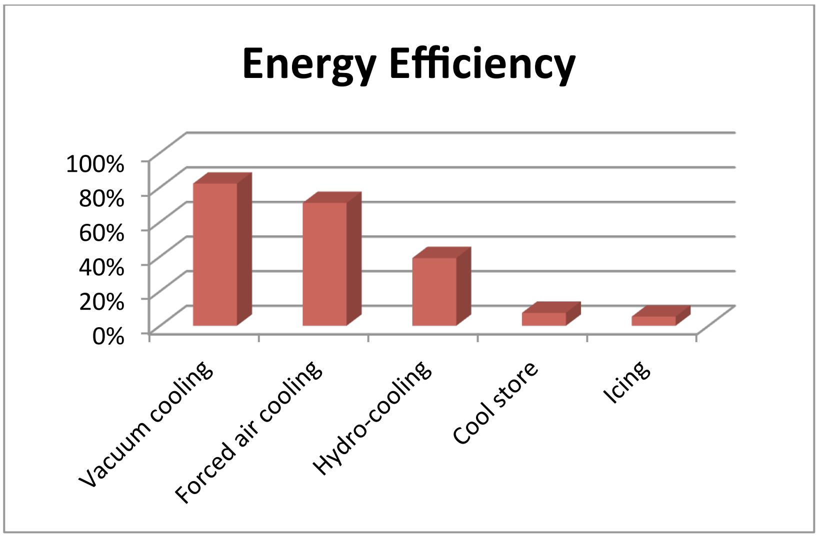


Cool store efficiencies are increased markedly when the floor is insulated from the ground. Assumptions used in this analysis uses investigations in 2014 that indicated most cool store floors were uninsulated.

6.8. Summary

Broccoli cooling methods show varying energy efficiencies and cooling rates, as indicated on the following table.

Broccoli cooling 20 to 4°C	MJ/ Tonne	Energy Efficiency	Cycle time	Electrical Energy Cost
Theoretical	64	100%		$ 4.48
Vacuum cooling	78	82%	60 min.	$ 5.46
Forced air cooling	90	71%	8 hours	$ 6.31
Hydrocooling	136	47%	30 min.	$ 9.49
Cool store	858	7%	14 days	$ 60.06
Icing	1218	5%		$ 85.26



This data consists of estimates from field data, which can vary considerably in individual circumstances. However, the basic conclusions that can be drawn are that:

- Hydrocooling may be the quickest, but it costs more in energy used
- Vacuum cooling is fairly quick and is the most energy efficient
- Forced air-cooling in a cool store is slower and in the middle range of efficiency
- Icing is comparatively slow and very costly
- Cool storage can be very inefficient if cooling takes weeks.

Field data consolidated at the University of Davis CA[38], USA confirms these basic findings and indicates a wide variation in individual energy efficiencies for growers. In study by Thompson and Chen[39] of comparative energy efficiencies of cooling methods for fruits and vegetables vacuum cooling was found to be the most energy efficient method of cooling followed by hydrocooling and forced air. They found hydrocooling efficiencies varied by 50% around the average due to site specific issues.

One of the largest site-specific issues is the coefficient of performance (COP) of refrigeration systems. The average used in these calculations is a COP of 0.7, or Heat transfer / electrical energy = 0.7. Modern chiller systems employing VSD controls, ammonia as a refrigerant, EC motors and screw compressors can achieve a COP of 2 to 4. Employment of these efficient refrigeration systems can turn the electrical energy demand around, but does not change the basic energy efficiency in MJ of the cooling methods examined.

[38] 2006 survey of electrical consumption data for vegetable growers in California available at: WWW.UCANR.edu/datastoreFiles/234-1165.pdf

[39] Comparative Energy Use of Vacuum, Hydro, and Forced Air Coolers for Fruits and Vegetables by Thompson and Chan available at: UCCE.ucdavis.edu/files/datastore/234-1044.pdf